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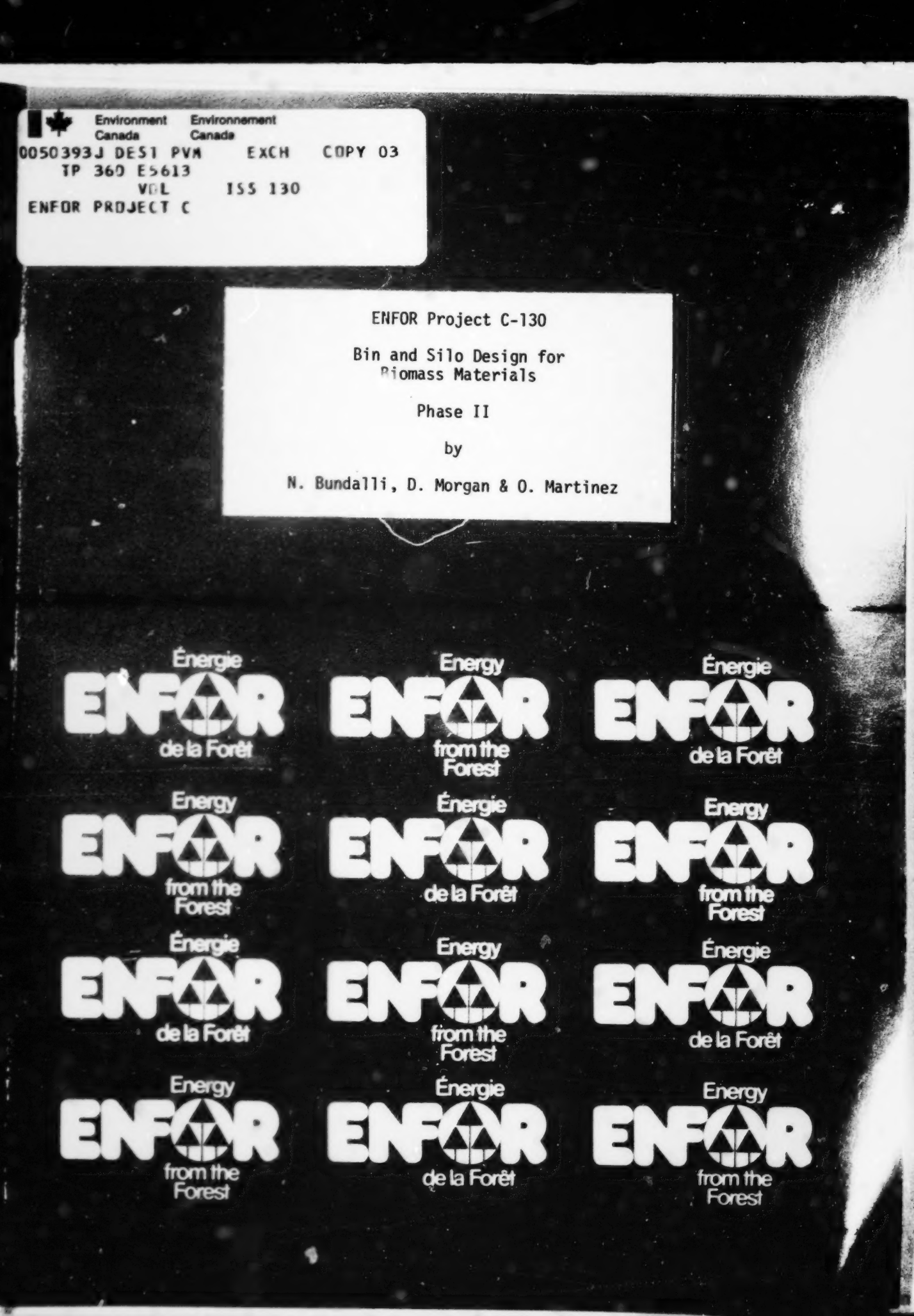
ENFOR Project C-130

Bin and Silo Design for Biomass Materials

Phase II

by

N. Bundalli, D. Morgan & O. Martinez



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ENFOR Project C-130

Bin and Silo Design for Biomass Materials

Phase II

by

N. Bundalli, D. Morgan & O. Martinez

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SUMMARY

An experimental bin was designed and constructed to enable confirmation of results obtained during Phase I of the project (1) on critical bin parameters necessary for reliable discharge of biomass materials. Discharge tests were carried out on three different types of hog fuel and one type of wood chip. Flowability tests were also carried out on laboratory equipment for comparison.

Results confirm that simple gravity discharge is possible from outlets that are practical provided that the hopper is of mass flow design. Flow is possible even after storage at rest for periods of at least several weeks without any external flow promoting devices. Ultra high molecular polymer and glass-coated steel, which were both used as bin liners, were found to be suitable for lining mass flow hoppers for biomass. It is anticipated that both those materials can withstand wear and tear under normal service.

Problems were experienced with the triple screw feeder built for discharging the bin contents, primarily due to the much larger than anticipated feeder loads. Tests were carried out without the feeder, by using a simple plywood gate.

Feeder performance is considered crucial to effective utilization of the mass flow design principles. A feeder must withdraw material uniformly from the whole outlet area as any stagnant zones will lead to bridging. Sufficient information on effective feeder design is not available for the large openings that are necessary for biomass materials. Attention must be given to this area to minimize problems.

EXECUTIVE SUMMARY

A plain-flow type experimental bin with a capacity of 80 m^3 (15 units) was designed and constructed to allow confirmation of Phase I results of the project on critical bin parameters necessary for reliable flow. The bin has a 4.6 m long rectangular opening; the width of the opening can be varied from 0.5 m to 1.5 m. The two sloping sides of the hopper can be set at 20° or 30° to the vertical. The bin walls have been lined with ultra high molecular polymer (UHMP). Midway through the test program, panels of glass-coated steel were placed directly over the UHMP on the two sloping sides. UHMP and glass-coated steel were selected because of their low wall friction against most types of biomass. The bin was equipped with a variable pitch triple screw feeder to allow a controlled discharge.

Problems were experienced with the feeder, primarily due to much higher than anticipated loads on the feeder. The feeder was removed for strengthening of shafts and bearings. In the meantime, tests were continued without the feeder, by using a simple plywood gate and discharging the bin contents to the floor. Tests were done with 3 different types of hog fuel and one sample of Cedar chips.

Results confirmed the major conclusion of Phase I, that is, simple gravity discharge of most biomass materials, including hog fuel and wood chips, is feasible from storage bins of mass flow design. The outlet sizes that were necessary for flow were considerably smaller than those predicted from shear tests and, hence, even more practical. Discharge of hog fuel is feasible under gravity alone even after storage at rest for periods of several weeks. Even the worst type of hog fuel was found to flow under gravity alone. Hence, the only condition for which some form of flow assistance may be necessary is freezing. Tests were not carried out under freezing conditions for practical reasons.

UHMP and glass were found to be both suitable as mass flow hopper liners. Fastening of UHMP was found to be a problem due to its higher coefficient of expansion compared with steel. The glass-coated steel panels had a coating of approximately 0.2 mm thick layer of glass baked on to thick gauge steel sheets. No visible sign of wear or cracking of the coating was evident in spite of considerable flexing of the steel walls under load. Hence, it appears that both materials can withstand wear and tear under normal service. Longer term tests including accelerated wear tests are desirable, especially for glass-coated steel which is a relatively new material for the forest industry.

The critical outlet dimensions based on the results of the tests are revised downwards from those recommended earlier (1). The minimum outlet dimensions recommended for hog fuel are 1.5 m to 3 m diameter for conical hoppers, depending on the flowability of the hog fuel (the equivalent rectangular or oval outlets for plain-flow hoppers are 0.7 m x 2.1 m to 1.5 m x 4.5 m). An outlet diameter of 1.5 m (0.7 m x 2.1 m for plain-flow hopper) is considered adequate for wood chips. Most types of sawdust will require minimum outlet diameters of 0.7 m for conical hoppers. The maximum hopper wall angles to the vertical recommended for biomass are 20° for conical hoppers and 25° for plain-flow hoppers, when using UHMP or glass-coated steel as liners.

Effective feeder operation is essential for mass flow discharge. A feeder must draw material from the full area of the opening as any stagnant zones will result in bridging. Lack of design information on effective feeding, particularly for the large outlet dimensions necessary for biomass, became evident during the design of the screw feeders. Careful attention must be given to bin and feeder parameters that affect uniformity of feeding. Large outlet dimensions and, in particular, long slots must be avoided to minimize the above problem.

Feeder loads will be considerably higher for mass flow bins and, hence, it will be necessary to design for higher mechanical strength and power.

During the last month of the project, the triple screw feeder was re-installed after being strengthened. The 22 kW (30 horsepower) motor was found to stall when an attempt was made to operate the feeder under load. Extensive modifications to the feeder were not within the scope of the existing project and, hence, no further testing with the feeder was carried out.

INTRODUCTION

The diminishing of world petroleum reserves has made the development of alternative, domestic energy sources an important part of Canada's drive towards energy self-sufficiency. The Canadian forests are a potential source of perpetually renewable fuels and chemicals. To promote increased utilization of biomass, the Canadian Forestry Service started the ENFOR R & D program in 1978 aimed at securing necessary knowledge and technical competence. This program is currently administered by the Energy, Mines and Resources Department. The program consists of two sub-programs:

1. The Production Program which is concerned wih forest-oriented matters such as biomass inventory, silviculture, harvesting and environmental impacts.

2. The Conversion Program which is concerned with the transformation of the biomass to energy, prepared fuels in various forms as well as chemicals.

Operation of pilot-scale biomass energy conversion plants revealed serious problems in the materials handling area and as a result, emphasis was placed on R & D aimed at solving these problems. A major materials handling problem has been the lack of reliable and uniform discharge of biomass from storage bins and silos. Stoppages in flow are common, resulting in disruptions to the operation of energy conversion plants.

Starting in April 1980, B.C. Research has been involved in an ENFOR project aimed at determining factors affecting the flow of biomass materials from bins and silos and to derive guidelines for improved designs. This report covers work done during the second phase of the project. Phase I of the project consisted primarily of determining the flow characteristics of a range of biomass materials using specially constructed laboratory test equipment and to predict critical bin and silo design parameters that have to be exceeded in order to obtain reliable and uniform discharge of biomass.

Results of Phase I (1) showed that the majority of biomass materials had too high an internal friction to permit the flow of material over itself (funnel flow). Hence, designs that rely on funnelling of material in the bin will not work in the absence of external flow promoting devices. On the other hand, mass flow bin design, where the material flows over the bin walls with little interparticle movement, was found to be feasible. For hog fuel and wood chips, the minimum outlet dimensions predicted were considerably smaller than those used in the industry.

Mass flow bin design is characterized by smooth, steep hopper walls, the wall angle being dependent on the friction of the biomass material against the appropriate wall material. For the majority of biomass materials the wall friction against conventional bin wall materials (concrete and steel) was found to be very high and, hence required impractical hopper angles. Hopper liners or coatings that reduced wall friction considerably were found to be essential. Of the liners tested, only two were found to have low enough friction - ultra high molecular polymer (UHMP) and a glass coated steel.

Hog fuel was found to gain in strength considerably following time consolidation in the test equipment. The openings predicted for storage at rest were found to be too high to be practical. This result would limit the storage of hog fuel to small surge bins.

It was felt necessary to confirm and demonstrate the above results in a realistic size experimental bin. The critical bin parameters predicted from laboratory test equipment were felt to be on the conservative side as procedures for calculating these parameters had built-in safety factors. It was also felt necessary to determine the extent of the safety margin, particularly for the storage at rest condition for hog fuel, which was found to be very limiting.

MATERIALS AND METHODS

DESIGN OF EXPERIMENTAL BIN

The following criteria were used in designing the experimental bin:

1. Bin Size

Cost considerations made it necessary to have the bin as small as possible. At the same time the bin was to be of a realistic size, approaching that of a small surge bin used in the forest products industry. It was also necessary to have deep enough converging and vertical sections to properly observe flow through the hopper and to have sufficient head of material above the outlet. A minimum 3:1 ratio of the bin width at the top to the outlet width was felt to be necessary.

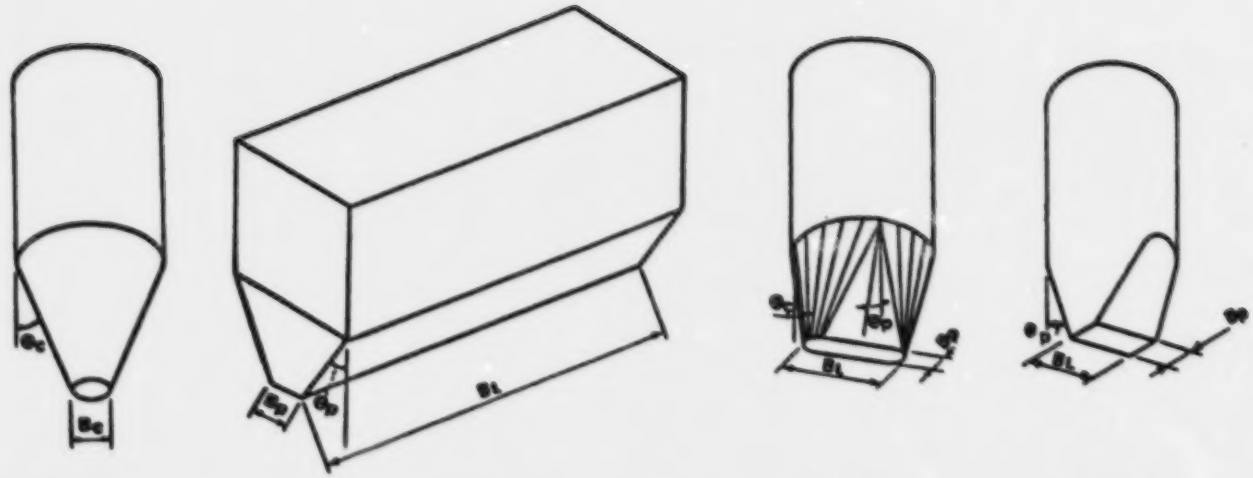
2. Bin Shape

The choice of shape was from the following main types of mass flow bins (see Figure 1):

- circular bin with a conical hopper,
- plain-flow bin with all flat sides,
- circular bin with transition hopper and oval outlet,
- circular bin with a "chiselled" hopper section.

A rectangular plain-flow bin was chosen because of the ease of lining the flat sides in comparison with curved sides. Other factors favouring this choice were the ease of adjusting the outlet size and hopper slope, as explained below. Also, a plain-flow hopper enabled use of a hopper approximately 10° less steep.

Fig 1 MASS FLOW BIN CONFIGURATIONS



3. Outlet Size and Hopper Slope

The maximum opening selected must allow flow of most types of hog fuel following storage at rest of about 3 hours. The slope of the hopper must be a minimum of 30° to the vertical to enable mass flow over a UHMP liner.

Both the outlets and the slopes must be adjustable in order to determine the extent of safety margins built into the minimum openings predicted from laboratory tests. The use of glass coated steel required a hopper slope to the vertical of 20°.

4. Loading Time

It was felt necessary to be able to load the bin within 3 hours in order to prevent excessive gain in strength at rest. Laboratory results of Phase I had indicated that discharge problems would be experienced over longer rest periods.

5. Controlled Discharge of Bin

Controlled discharge of the bin by means of a feeder was desirable for the following reasons:

- ease of bin discharge,
- withdrawal of material via a feeder is a more common way of discharging a bin,
- the feeder could be used to discharge the bin very slowly and to recycle the material into the bin in order to overcome the problem of time consolidation of material.

As explained later in the report, provision was made to allow for emptying of bin contents without a feeder in order to assess the bin independantly of the feeder.

6. Other Considerations

The movable bin walls were to be light enough to allow handling with a one ton hoist.

FEEDER DESIGN AND SELECTION

Feeder performance is very critical for a mass flow bin to work effectively. The main requirement of a feeder is that material is drawn from the full slot. Any stagnant areas will quickly lead to stoppage in flow as material is required to flow over itself.

It became apparent early in the project that feeder design for biomass bins was a grey area with little information available for effective feeding. Design guidelines available applied for bins for fine powders or granular materials which required outlets that were less than one-third of those required for biomass bins.

With the uncertainty in the performance of a feeder, the decision was made to raise the bin an extra metre to allow sufficient room under the bin to discharge material to the floor by means of a simple gate. Hence, the critical bin parameters for mass flow could be assessed independently of the feeder performance.

A triple-screw feeder was selected since it would allow a three-step change in the width of the opening by discharging over one, two or three screws. Effective feeding would be attempted by varying the pitch over the length of the slot opening. Variable diameter flights were also considered since these would also assist in effective feeding; owing to the high cost, it was decided to use constant diameter screws.

DESCRIPTION OF EXPERIMENTAL BIN

Figure 2 shows a drawing of the experimental bin designed and built for the project. Figure 3 shows a photograph of the bin with the loading and discharge conveyors in place. The bin is 4.6 m square at the top with a 1.2 m vertical section. The hopper walls are 3.0 m long and converge at 20° or 30° to the vertical to a 0.5 m or 1.0 m or 1.5 m wide slot opening. The maximum capacity of the bin is 80 cu. m.

All of the bin walls have been lined with UHMP which was fastened to the steel walls by means of elevator bolts. The bolt heads were recessed into the plastic to a flush finish. For tests with glass-coated steel which were carried out mid-way through the testing program, 8 panels each 3.2 m x 1.1 m x 1.8 mm thick were laid directly on top of UHMP on the two converging hopper walls. The panels were bolted at the top only at locations where the fasteners were not in contact with material in the bin.

The discharge feeder consists of three parallel 0.48 m constant diameter variable pitch screws. The pitch varies in five discrete steps ranging from half pitch (0.25 m) to full pitch (0.50 m). Figure 4 shows a view of the UHMP lined walls and the parallel screw feeder.

Feeder design for mechanical strength and power requirements were based on information published by the Conveyor Equipment Manufacturers' Association (CEMA) (2).

An existing 0.30 m wide conveyor belt was lengthened and installed for loading material into the bin. The conveyor has a hopper at the lower end where material can be dumped by a Bobcat.

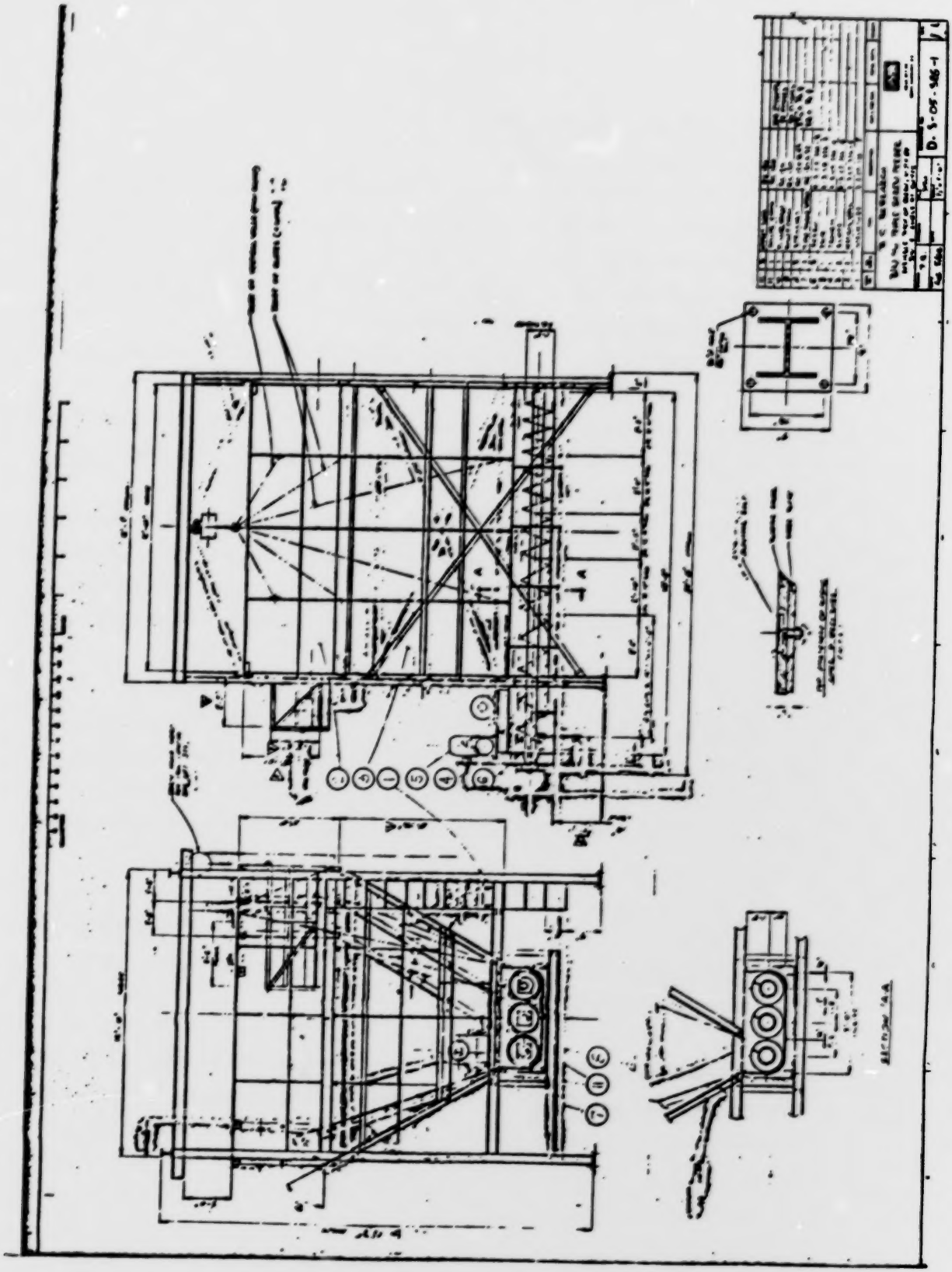


FIGURE 2. DRAWING OF THE EXPERIMENTAL BIN

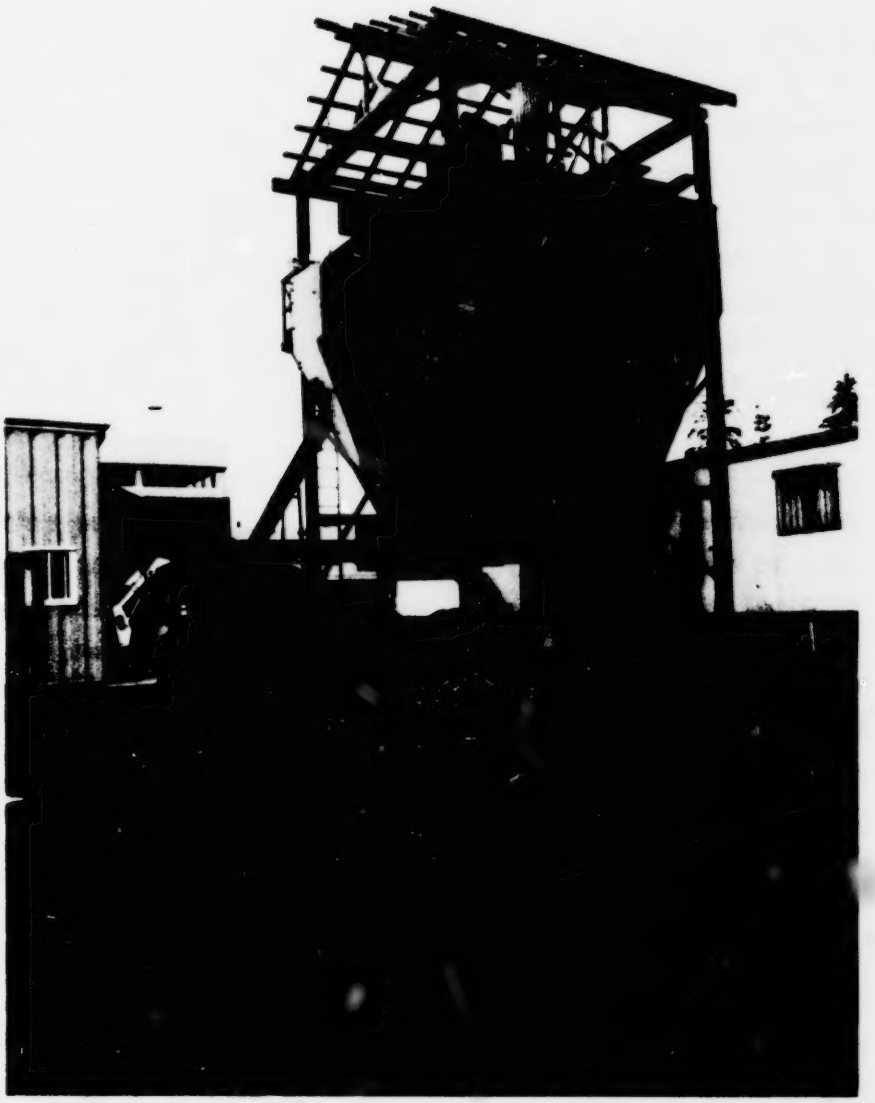


FIGURE 3. PHOTOGRAPH OF THE EXPERIMENTAL BIN, FEEDER AND CONVEYORS

FIGURE 4. VIEW OF THE UHMP LINED WALLS
AND THE TRIPLE SCREW FEEDER

TESTS WITH BIOMASS

Start-up Tests

The first set of tests were done with hemlock hog fuel using the screw feeder to discharge the materials. Approximately 30 cu. m. of hog fuel was loaded into the bin. When an attempt was made to discharge the bin, one of the shafts bent and a bearing cracked; the equipment was turned off immediately to prevent futher damage. It was obvious that the feeder did not have sufficient mechanical strength to withstand the load exerted on it. The load on the feeder was much higher than anticipated primarily due to the mass flow design which transferred most of the weight of hog fuel from the bin walls to the feeder. The feeder was removed for strengthening.

At this point, a decision was made to test the bin without the feeder as the bin design project was quickly turning into one of feeder design also. The strengthened feeder would be tested towards the end of the project once the major objectives of verifying the critical outlet dimensions and mass flow hopper slopes were completed.

It was necessary to design a simple gate that could be closed to allow the bin to be filled; material could be discharged by releasing the gate. After considering several gate designs, a simple plywood gate consisting of boards propped-up by wooden posts, as shown in Figure 5, was chosen. The design of the posts were refined to the point where all the posts could be made to collapse simultaneously, thereby discharging the material over the full opening. This method of loading and discharging the bin contents was found to work quite satisfactorily and was used for the majority of the tests.

Bin Discharge Tests

Tests were done using three different types of hog fuel and one type of wood chip.

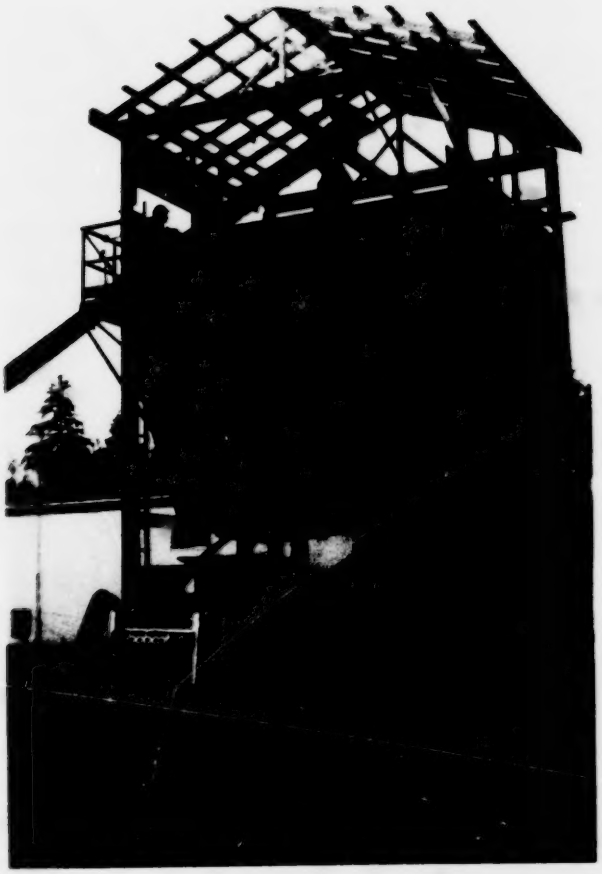


FIGURE 5. SET-UP OF BIN DISCHARGE TESTS WITH PLYWOOD GATE

Prior to each test, the width of the bin opening was set at either 0.5 m, 1.0 m or 1.5 m and the hopper slope was set at 20° or 30° to the vertical. The gate was placed in position at the opening and material loaded into the bin. The loading time was 3 to 4 hours and, hence, this was the minimum storage at rest time. Following a predetermined storage at rest period of the material in the bin which ranged from 3 hours to a week attempt was made to discharge the contents of the bin by pulling away the supporting posts of the gate. Observations were made of the flow and the pattern of discharge of the material in the bin.

Altogether 14 tests were done of which two were on wood chips. Tests were done using both the UHMP liner and the glass-coated steel panels on the bin walls.

The hog fuel and chips samples tested were as follows:

1. Sample 1 - Hemlock hog fuel

   This was a typical hemlock hog fuel which was a mixture of large chunks of wood as well as very fine bark. The material had a high moisture content and a high bulk density. Laboratory tests during Phase I of the project had indicated that such a material would be relatively easy flowing.

2. Sample 2 - Stringy Cedar Bark

   Since results with sample 1 were very encouraging, the next series of tests were done with stringy cedar bark which is considered to be the worst hog fuel to handle.

3. Sample 3 - Dry Cedar Hog Fuel.

   Results with this material are felt to be important to companies that dry hog fuel; the low bulk density will normally require larger openings.

4. Sample 4 - Cedar Chips

   Cedar was chosen because of its low cost; results will be applicable to other species of chips also.

For a selected number of tests, photographs were taken at the discharge end; views from the top of the bin as well as the discharge end were also recorded on video for some of the tests.

Shear and wall friction tests were done for each of the samples of biomass tested. Moisture content and particle size distributions were also determined.

RESULTS

All of the components of the experimental bin excluding the screw feeder but including the loading system and the gate discharge system performed satisfactorily and very useful data were obtained on the range of bin outlet widths and the hopper slopes that are necessary for uniform and reliable flow.

Results of the bin discharge tests are shown in Tables 1 to 4 for each of the samples of hog fuel and wood chips. As shown in the tables, successful mass flow discharge was possible for all of the hog fuel and chip samples tested using at least one of the available outlet dimension and hopper slopes.

Figures 6 to 9 show photographs taken at the discharge end of the bin during some of the tests. It was not practical to take photographs from the top, looking into the bin; however, video shots* taken from this position show quite clearly the mass flow pattern of discharge whenever flow did take place. When the hopper slopes were in the "non-mass flow" position, little movement of the material was observed, illustrating the enormous resistance of biomass to funnelling.

Detailed shear and wall friction test results for the biomass materials tested in the experimental bin are given in Appendix A. Critical bin parameters evaluated from the test results are summarized in Table 5 alongside outlet dimensions and hopper slopes that were necessary for flow to take place in the experimental bin.

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*The video shots can be made available by special arrangement with B.C. Research

TABLE 1

SUMMARY OF TEST RESULTS WITH HEMLOCK HOG FUEL (SAMPLE 1)

- Bin Liner - UHMP
- Mean particle size, 9.5 mm
- Moisture content 63-64%

TEST NO.	HOPPER ANGLE TO THE VERT, p (see Figure 1)	WIDTH OF BIN OPENING, m	APPROX. VOL. OF MATERIAL IN BIN, cu. m.	APPROX. STORAGE AT REST, Hours	OBSERVATIONS
1	20	1.0	40	7	Successful mass flow discharge.
2	20	1.0	65	7	Successful mass flow discharge.
3	20	0.5	25	5	Mass flow discharge - quantity of material in the bin was very small for meaningful test.
4	20	0.5	50	5	Repeat of test above with more material. Bin discharged only partially; the remaining bridged.
5	30	1.0	65	4	Successful mass flow discharge; material was considerably finer due to handling from previous tests.
6	30	1.0	65	48	Successful mass flow discharge after 2 days storage.
7	30	1.0	80	48	Above tests repeated with bin completely full; successful mass flow discharge.

TABLE 2

SUMMARY OF TEST RESULTS WITH STRINGY CEDAR BARK (SAMPLE 2)

- Bin Liner - UHMP
- Mean particle size, 14.0 mm
- Moisture content 50%

TEST NO.	HOPPER ANGLE TO THE VERT, p (see Figure 1)	WIDTH OF BIN OPENING, m	APPROX. VOL. OF MATERIAL IN BIN, cu. m.	APPROX. STORAGE AT REST, Hours	OBSERVATIONS
1	30	1.5	40	4	Very little flow. Material formed a stable bridge which was hard to clear.
2	20	1.5	50	4	Above test repeated with steeper hopper; successful mass flow discharge.
3	20	1.5	60	48	Above test repeated after 48 hours storage at rest; successful mass flow discharge.
4	20	1.0	65	72	Above test at smaller opening; material bridged but appeared to be on the verge of flowing. Bin was easily cleared.

TABLE 3

SUMMARY OF TEST RESULTS WITH DRY CEDAR HOG FUEL (SAMPLE 3)

- Bin Liner - glass-coated steel
- Mean particle size, 4.4 mm
- Moisture content 45%

TEST NO.	HOPPER ANGLE TO THE VERT, p (see Figure 3)	WIDTH OF BIN OPENING, m	APPROX. VOL. OF MATERIAL IN BIN, cu. m.	APPROX. STORAGE AT REST, Hours	OBSERVATIONS
1	20	1.0	65	30	Fuel had been double-hogged and dried in a flue gas drier. Successful mass flow discharge. Material flowed very easily and no further tests were necessary.

TABLE 4

SUMMARY OF TEST RESULTS WITH CEDAR CHIPS (SAMPLE 4)

- Bin Liner - glass-coated steel
- Mean particle size, 14.5 mm
- Moisture content 52%

TEST NO.	HOPPER ANGLE TO THE VERT, θ_p (see Figure 1)	WIDTH OF BIN OPENING, m	APPROX. VOL. OF MATERIAL IN BIN, cu. m.	APPROX. STORAGE AT REST, Hours	OBSERVATIONS
1	20	1.0	65	6	Successful mass flow discharge.
2	20	0.5	65	24	Above test repeated with smaller opening. Successful mass flow discharge. Only a very small quantity of material was hung up around an unfilled hole in the liner.

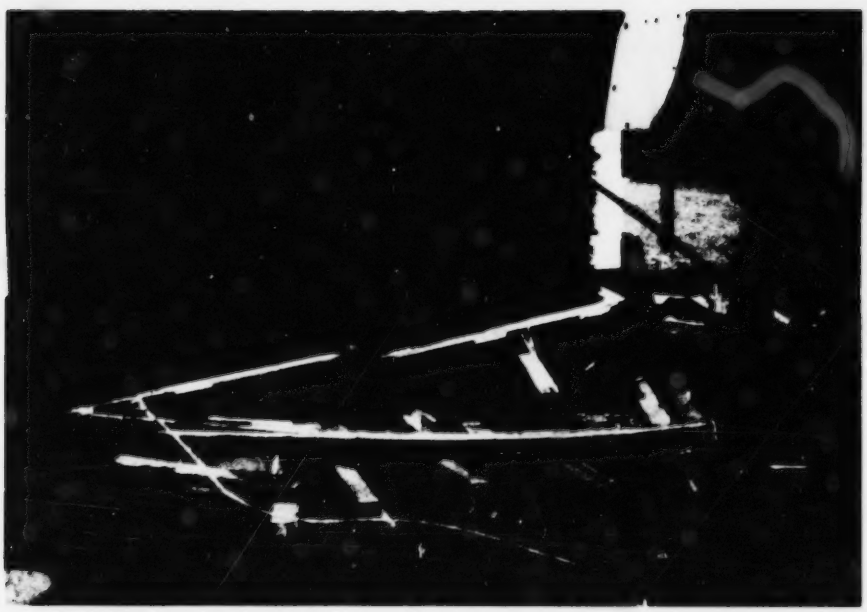


FIGURE 6. DISCHARGE OF HEMLOCK HOG FUEL FROM 100 CM WIDE OPENING

(See Table 1, Test 2)

FIGURE 7. ATTEMPT AT DISCHARGE AND BRIDGING OF HEMLOCK HOG FUEL FROM 50 CM WIDE OPENING

(See Table 1, Test 4)

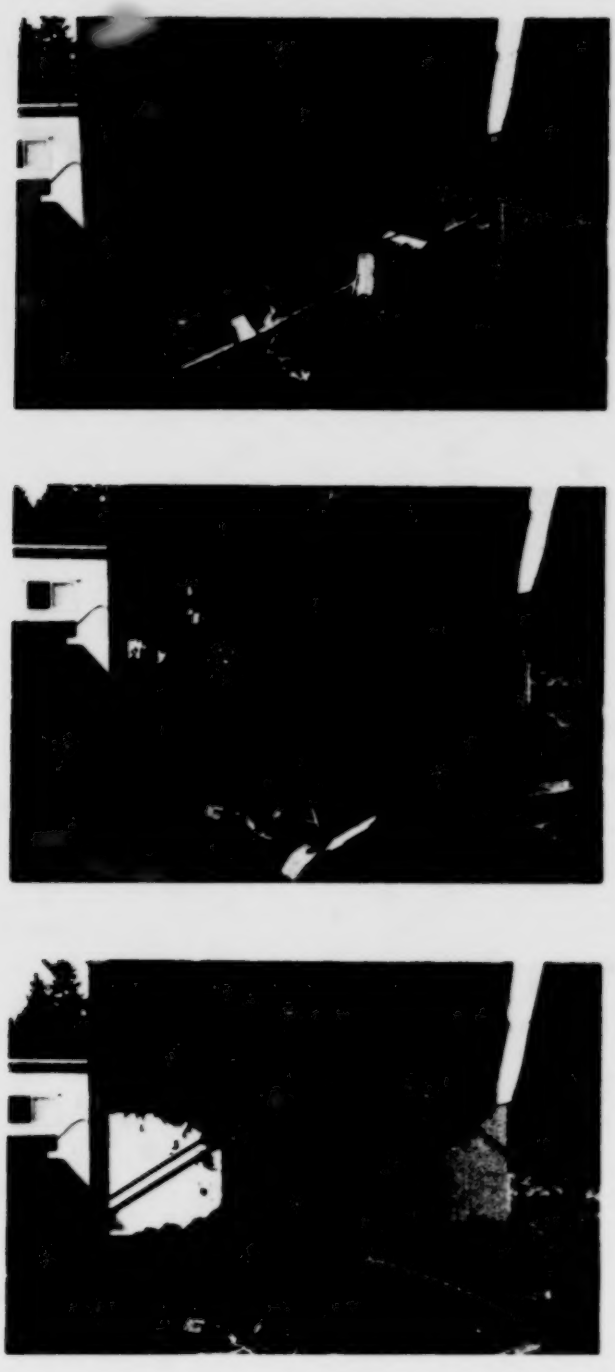


FIGURE 8. ATTEMPT AT DISCHARGE AND BRIDGING OF STRINGY CEDAR BARK THROUGH 100 CM WIDE OPENING

(See Table 2, Test 4)

FIGURE 9. DISCHARGE OF CHIPS THROUGH
100 CM WIDE OPENING

(See Table 4, Test 1)

TABLE 5

COMPARISON OF TEST RESULTS ON EXPERIMENTAL BIN
WITH PREDICTED CRITICAL BIN PARAMETERS

MATERIAL	SHEAR TEST RESULTS			RESULTS ON EXPERIMENTAL BIN		COMMENTS
	Minimum width of Opening Predicted, m		Maximum Hopper Angle to the vertical, degrees	Width of Slot Opening for Flow, m	Mass flow Hopper Angle to the vertical, degrees	
	"Instantaneous" Consolidation	After Time Consolidation				
1A. Hemlock Hog Fuel	0.83	1.38	30 (UHMP)	1.0	30	Reasonably "free flowing" material because of its high bulk density
1B. Hemlock Hog Fuel	0.84	3.45	30 (UHMP)	1.0	30	Same material as above after 3 weeks outside storage and handling
2. Stringy Cedar Bark	3.93	5.20	25 (UHMP)	1.5	20	Worst material in terms of flowability; no flow with hopper angle set at 30° to the vertical
3. Dry Cedar Hog Fuel	0.67	1.37	25 (glass coating)	1.0	20	"Double-hogged" dry Cedar; relatively free flowing material
4. Cedar chips	1.50	1.50	25 (glass coating)	0.5	20	Typical screened chips

Performance of Liners

There was no visible sign of wear on either the UHMP or glass-coated steel liner at the end of the tests. UHMP was found to have warped somewhat in places due to differential expansion and precautions had to be taken to ensure that material did not get caught at the seams between sheets of the liner.

The glass coating of approximately 0.2 mm on steel was found to resist cracking in spite of the considerable flexing of the hopper walls under load.

Tests with the Strengthened Feeder

During the last month of the project, the screw feeder was re-installed. Attempts to operate it with the bin full of material were not successful as it resulted in the stalling of the 22 kW (30 horsepower) motor. Extensive modifications to the feeder were not within the scope of the existing project and no further tests were attempted with the feeder. Hence, no data was available on the suitability of the variable-pitch screw feeder for uniform withdrawal of material.

DISCUSSION

GRAVITY DISCHARGE OF BIOMASS

Tests on the experimental bin have confirmed the major conclusions of Phase I of this project, which are:

1. Simple gravity discharge of biomass is feasible from bins and silos with converging hoppers. Even the most difficult flowing hog fuel can be discharged under gravity alone.

2. The hoppers must be of mass flow design, i.e., the hopper walls must be steep and smooth enough to allow material to slide over the walls in preference to funnelling over itself. Most types of biomass have enormous resistance to funnelling and cannot be made to flow through hoppers with inadequate slopes and smoothness.

3. Ultra high molecular polymer (UHMP) and glass coated steel have excellent frictional characteristics against biomass. Both these materials are very suitable as hopper wall liners for biomass bins and silos, enabling use of very practical hopper slopes. Conventional bin wall materials (steel and concrete) on their own are not suitable for hog fuel and wood chips because of high frictional resistance.

The fact that hog fuel can flow through a converging hopper is very significant. Attempts at solving flow problems of hog fuel have been to use negative slope hoppers with large openings in the belief that hog fuel will compact and plug up in a converging hopper. Negative slopes lead to very large openings and invariably result in stagnant zones at the outlet because of the difficulty in feeding effectively from a large area. Ineffective feeding is an important contributor to discharge problems of biomass bins and silos.

Use of a converging mass flow hopper will enable reduction in the size of the opening. For biomass materials generally, it is desirable to stay as close as possible to the minimum outlet dimension in order to minimize feeding problems. An added benefit will be lower cost of feeding equipment for a smaller opening. (Problems of feeding are discussed later on in this section).

Results on the experimental bin have shown that minimum outlet dimensions predicted from shear tests carried out during Phase I were overly conservative, particularly for storage at rest of hog fuel. The minimum outlet dimension to prevent bridging in a mass flow bin is considerably smaller and, hence, even more practical. Hog fuel was found not to pick up excessive strength during storage at rest as was indicated by shear test results. This means that longer term storage of hog fuel in large bins and silos is feasible. Earlier results had indicated that only transient storage of hog fuel in small surge bins was feasible.

For a conical mass flow hopper with a circular opening (see Figure 1), a minimum outlet diameter of 2 m will be sufficient to allow flow of the normal hog fuel types. The equivalent outlet dimensions for a plain flow hopper (see Figure 1) are 1 m x 3 m. For hog fuel with poor flow characteristics such as stringy cedar bark, an opening of 3 m for a conical hopper (1.5 m x 4.5 m for a plain-flow hopper) should be sufficient to prevent bridging.

Mass Flow Hopper Angles

The mass flow hopper angles predicted from wall friction tests were also confirmed on the experimental bin. With the UHMP liner, hopper wall angle (see Figure 1) of 30° to the vertical (60° to the

horizontal) allowed mass flow discharge of Hemlock hog fuel from the plain-flow bin. For the stringy Cedar bark, however, it was necessary to have a steeper hopper (20° to the vertical) in spite of only slightly higher wall friction of the latter. Possible explanation of this is that a wall angle of 30° to the vertical is considered a maximum for mass flow for either conical or plain-flow hoppers regardless of wall friction results. Safety margins of several degrees from this angle may be necessary to ensure mass flow.

Hence, allowing a 5° margin for safety, a hopper wall angle of 25° to the vertical for both UHMP and glass-coated steel is considered to be adequate for a plain-flow hopper. For a conical hopper, a maximum 20° to the vertical will be necessary with the same liner materials.

FEEDER PERFORMANCE AND DESIGN

Problems were experienced with the triple screw feeder designed for discharging biomass from the bin. The load on the feeder as well as the power required to operate it were considerably higher than the values calculated according to CEMA design guidelines (2). The feeder shafts and bearing were strengthened considerably after their initial failure. The 22 kW (30 horsepower) motor was, however, found to be inadequate to operate the feeder. The scope of the existing project did not allow for extensive modifications to the feeder to arrive at satisfactory operation.

Attempts at operating the feeder nevertheless provide valuable information on the problems created by mass flow design and to which careful attention must be given. The smooth, steep walls of a mass flow bin will result in much higher feeder loads and, hence, the feeder must be mechanically stronger and be equipped with a bigger motor in comparison with poorly performing bins.

Feeder performance is crucial to effective utilization of the mass flow design principles for biomass storage bins. A feeder must draw material from the full outlet as any stagnant zones will lead to stoppage in flow due to the inability of biomass materials to funnel. Full flow from the outlet is normally achieved by increasing feeder capacity in the direction of flow as shown in Figure 10. Published information on bin and feeder parameters to affect full flow were found to apply largely to granular and powdered materials which typically require outlets that are less than one-third of those required for biomass. Lack of suitable design information was particularly apparent for the screws in the experimental bin, which spanned a length of 4.6 m.

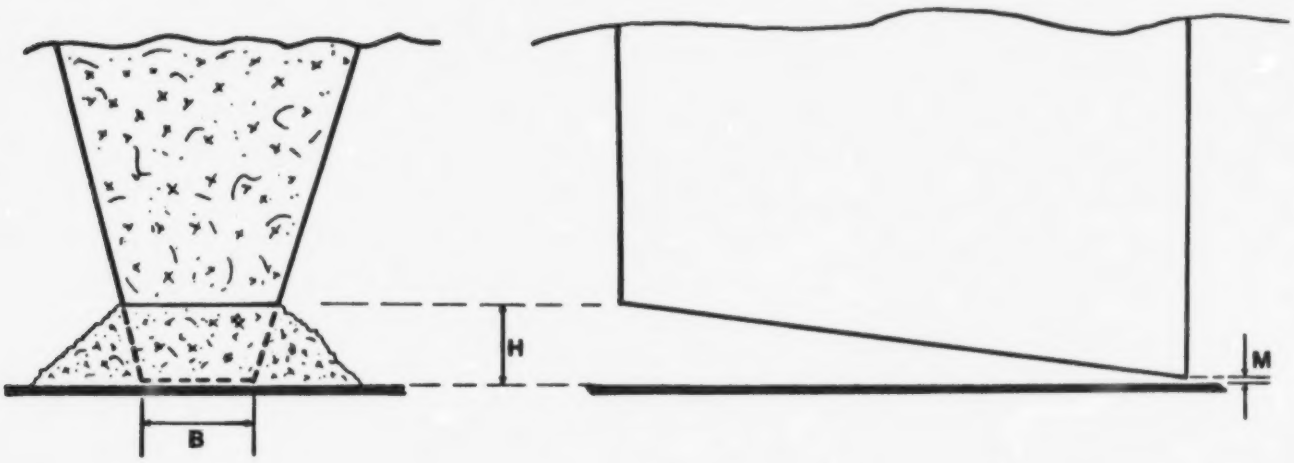
To minimize this problem, it is desirable to select the outlet to be as close to the minimum as possible. In particular, long, slotted outlets should be avoided as it is difficult to avoid stagnant zones. Provision must also be made in any bin-feeder designs to allow for modifications necessary for full flow at the outlet.

Performance of the Liners

The performance of both the UHMP and the glass-coated steel were satisfactory and it is anticipated that both the liners can withstand the wear and tear under normal service. UHMP is a more difficult material to fasten, particularly due to its tendency to warp. The glass coating is baked on to steel and welding can be done on the uncoated side without damaging the coating. The lower cost of this material in comparison to UHMP should make it an attractive bin liner material.

Longer term tests on the liners, including accelerated wear tests in the laboratory are desirable, especially for the glass-coated steel which is new to the forest products industry.

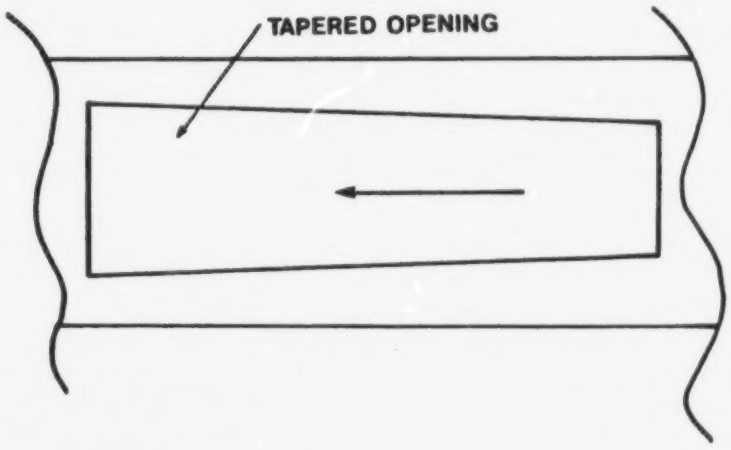
Fig 10 FEEDER DESIGN FOR A FULLY EFFECTIVE OUTLET



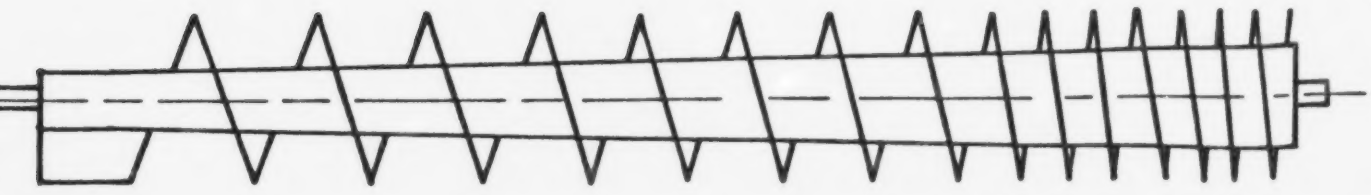
Hopper height at outlet

Minimum width for no-arching

Minimum clearance at rear



BELT OR CHAIN-TYPE FEEDER



SCREW FEEDER-VARIABLE PITCH, TAPERED SHAFT AND/OR VARIABLE DIAMETER FLIGHTS

CONCLUSIONS AND RECOMMENDATIONS

1. Simple gravity discharge of most biomass materials, including hog fuel and wood chips, is feasible from storage bins and silos of mass flow design. The outlet sizes necessary for uninterrupted discharge are considerably smaller than those predicted from shear test results of Phase I of this project (1) and, hence, even more practical. Discharge of hog fuel is feasible even after storage at rest for periods of at least several weeks; use of external flow promoting devices or recycling of hog fuel to maintain "instantaneous" conditions will not be necessary as recommended in the earlier project report. Hence, the only case where external flow promoting devices may be necessary are during freezing conditions.

2. For use of hopper slopes that are practical, special bin wall materials or liners with low wall friction against biomass will be necessary. Both UHMP and glass-coated steel are suitable for use in mass flow hoppers for biomass. Although long term service data are not available, it appears likely that both the materials can withstand normal wear and tear. Longer term tests are recommended, particularly for glass-coated steel which is new to the industry. Attention must be given to fastening of UHMP due to its tendency to warp from differential expansion. The glass-coated steel available has an approximately 0.2 mm thick coating of glass which is baked on to the steel. This material was found to have sufficient flexibility to withstand normal flexing without cracking. The glass-coated steel can be used on its own or as a liner in thin gauge steel.

3. Guidelines for minimum bin and silo outlet dimensions for hog fuel, wood chips and sawdust given below have been revised down from those recommended in the earlier Phase I project report. Tests are, however, recommended on actual biomass samples under consideration because of the high variability of biomass:

MATERIAL	MINIMUM OUTLET DIMENSION RECOMMENDED	
	CONICAL HOPPER	PLAIN-FLOW HOPPER
"Normal" hog fuel - 40-65% moisture content and without long stringy pieces or large chunks of wood	2 m	1 m x 3 m
"Easy flowing" hog fuel - fine hog fuel, preferably double hogged and 45 to 55% moisture content	1.5 m	0.7 m x 2.1 m
"Difficult" flowing hog fuel - e.g. stringy cedar bark	3 m	1.5 m x 4.5 m
Chips (most "normal" types, greater than 40% moisture content)	1.5 m	0.7 m x 2.1 m
Sawdust (greater than 40% moisture content)	0.7 m	0.4 M x 1.2 m

Hopper wall angles recommended for both UHMP and glass-coated steel are as follows:

	Conical Hopper	Plain-Flow Hopper
Wall angle to the vertical	20°	25°

3. Effective feeder operation is crucial to successful mass flow discharge. It is essential that a feeder withdraws material from the full area of the opening as any stagnant zones will result in bridging. The large outlet dimensions necessary for biomass materials in comparison with granular and powdered materials means that effective feeding will be more difficult to achieve. Most of the published information on feeding for the latter types of materials is not easily applicable to biomass materials. The

problem can be minimized however, by giving careful attention to bin-feeder parameters that affect uniform feeding:

- the outlet dimensions should be as close to the minimum as possible since feeding problems increase with the size of the opening;

- use of long slot openings should be avoided unless material can be fed from across the width of the opening (eg. via a travelling screw);

- in the case of belt or chain-type feeders, careful attention must be given to the bed height of material, H (see Figure 10) and the degree of taper of the opening;

- a screw feeder must have a variable pitch increasing in the direction of flow; for very long screws, it may also be necessary to have increasing diameter flights and/or tapered shafts (see Figure 10).

4. Feeder loads for mass flow bins will be considerably higher than those for poorly performing bins. It will be necessary to design feeders for higher mechanical strength and power.

5. Precautions outlined in the Phase I report (1) regarding the fastening of liners must be observed to ensure that flow of material is not obstructed.

REFERENCES

1. Bundalli, N. and O. Martinez, 1982. Bin and Silo Design for Biomass Materials. Enfor Project C-130, Enfor Secretariat, Ottawa, Ontario.

2. Conveyor Equipment Manufacturers Association, 1980. Screw Conveyors. CEMA Book No. 350. Washington, D.C.

STAFF

This project was carried out in the Physical Technology Division under the supervision of Mr. Nazmir Bundalli, P. Eng. Mr. Roy Farley, a consultant from the U.K. assisted in the interpretation of Phase I results and provided general guidance on the design of the experimental bin. Detailed design was carried out by Mr. Leonard Walker, P. Eng. and Mr. David Wallace, both of ACO Industries Ltd.; ACO also fabricated and assembled the experimental bin.

Tests on the experimental bin were performened by Mr. Duncan Morgan, Mr. Aldert Dykstra and Mr. Omar Martinez. The evaluation and interpretation of results and preparation of this final report was done by Mr. Bundalli.

ACKNOWLEDGEMENTS

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Macmillan Bloedel, Canadian White Pine Div., Vancouver
Terminal Sawmills, Vancouver.

ABSTRACT OF THE ABSTRACT

Critical mass flow bin parameters were confirmed for hog fuel and wood chips on a 80 m^3 capacity experimental bin.

APPENDIX A

DETAILED SHEAR AND WALL FRICTION TEST RESULTS
AND
PARTICLE SIZE DISTRIBUTIONS

TABLE A1 (a_0)

COMPUTER ANALYSIS OF FLOW PROPERTIES

HEMLOCK HOG FUEL SAMPLE # 1A

SHEAR TEST RESULTS

CONSOLIDATION		YIELD	
NORMAL STRESS	SHEAR STRESS	NORMAL STRESS	SHEAR STRESS
G/SQ CM	G/SQ CM	G/SQ CM	G/SQ CM
48.1	81.0		
		4.2	15.3
		8.4	22.6
		16.8	37.8
		27.0	51.9
		33.7	60.0
		39.6	75.5
		48.1	81.0
59.9	102.6		
		4.2	13.7
		8.4	24.8
		16.8	43.7
		27.0	63.6
		43.8	85.7
		56.5	93.4
		59.9	102.6
81.8	141.0		
		4.2	24.0
		12.6	33.4
		27.0	60.9
		56.5	98.8
		59.9	112.4
		73.4	115.4
		81.8	141.0
98.7	162.2		
		4.2	29.2
		12.6	37.9
		27.0	70.1
		56.5	112.3
		73.4	127.9
		90.3	140.4
		98.7	162.2
115.6	182.5		
		4.2	16.4
		12.6	40.6
		27.0	80.1
		56.5	105.0
		81.8	150.4
		107.1	156.6
		115.6	182.5

TABLE A1 (b_0)

HEMLOCK HOG FUEL SAMPLE # 1A

FLOW PROPERTIES OF MATERIAL

CONSOLIDATION				FLOW PROPERTIES				
NORMAL STRESS	SHEAR STRESS	MAJ PRINC CONSOL'N STRESS	UNCONFIN YIELD STRESS	FLOW FUNC	EFFECT FRIC ANGLE	INTERNAL FRIC ANG AT FREE SURFACE	COHESION	TENSILE STRENGTH
G/SQ CM	G/SQ CM	G/SQ CM	G/SQ CM		DEG	DEG	G/SQ CM	G/SQ CM
48.1	81.0	202.5	69.9	2.90	64.2	66.80	6.24	1.40
59.9	102.6	258.7	92.8	2.79	64.8	66.80	8.28	1.85
81.8	141.0	333.9	109.9	3.04	63.5	66.80	9.80	2.19
98.7	162.2	397.3	127.9	3.11	63.2	66.80	11.42	2.55
115.6	182.5	443.3	132.2	3.35	62.1	66.80	11.80	2.64

SHEAR INDEX (N) = 1.40

YIELD LOCUS	PERCENT FIT
1	99.6
2	99.6
3	99.5
4	99.7
5	99.3

TABLE A1 (d_0)

COMPUTER ANALYSIS OF STORAGE AT REST

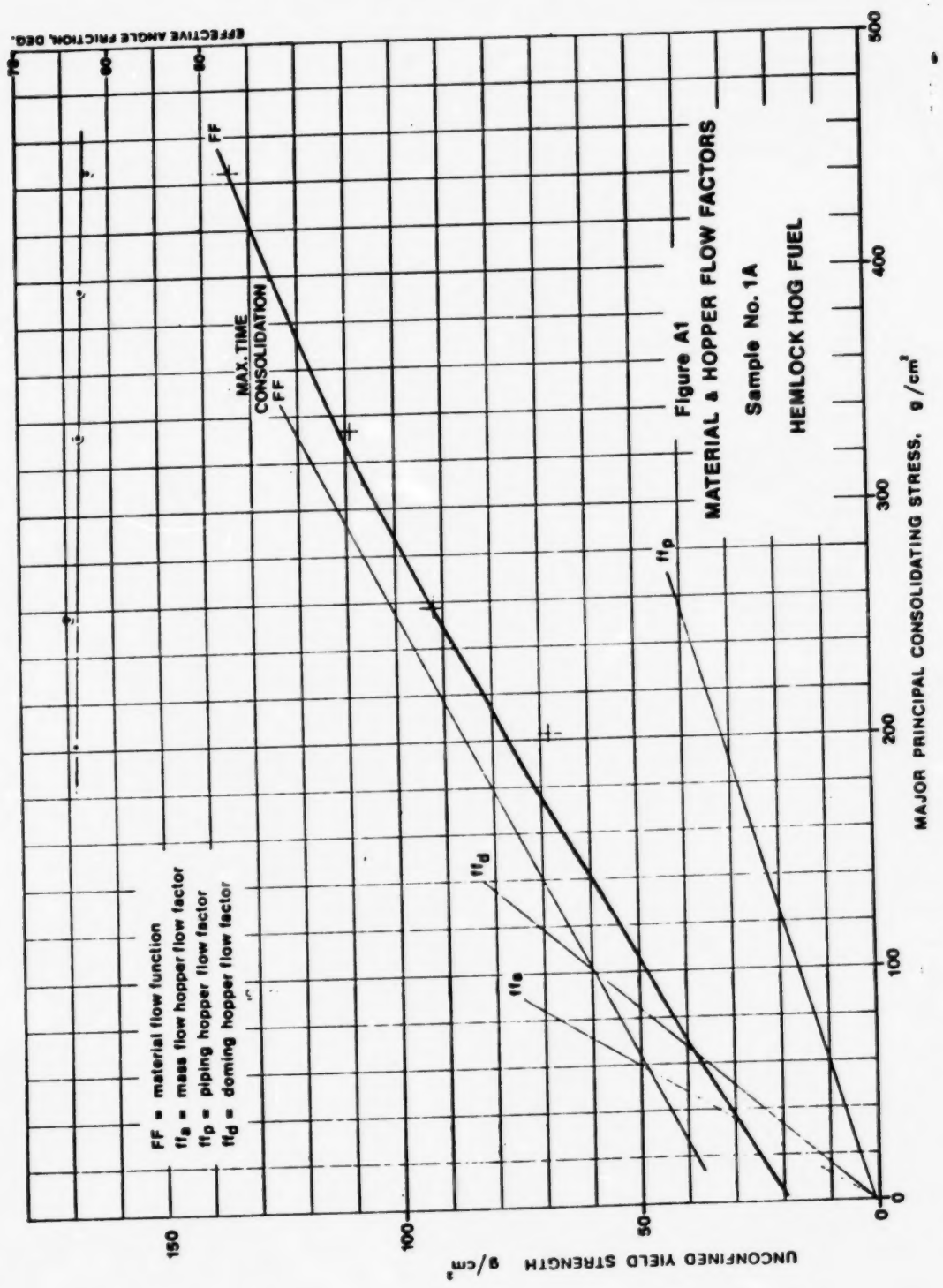
HEMLOCK HOG FUEL SAMPLE #1A

TIME CONSOLIDATION RESULTS

CONSOLIDATION		YIELD POINT		<----------FLOW PROPERTIES---------->					
NORMAL STRESS	SHEAR STRESS	NORMAL STRESS	SHEAR STRESS	MAJ PRINC CONSOL'N STRESS INST	MAJ PRINC CONSOL'N STRESS TIME	UNCONFIN YIELD STRESS	EFFECT FRIC ANGLE	INTERNAL FRIC ANG AT FREE SURFACE	COHESION
G/SQ CM	G/SQ CM	G/SQ CM	G/SQ CM	G/SQ CM	G/SQ CM	G/SQ CM	DEG	DEG	G/SQ CM
CONSOLIDATION PERIOD 3									
59.9	97.1	59.9	97.8	258.7	245.9	81.8	63.7	66.9	7.27
CONSOLIDATION PERIOD 5									
98.7	159.1	98.7	162.6	397.3	409.5	138.4	63.9	66.9	12.30
CONSOLIDATION PERIOD 16									
56.5	72.4	56.5	80.2	202.5	194.5	48.4	59.6	66.9	4.31
59.9	85.6	59.9	102.1	258.7	260.0	94.0	64.9	66.9	8.36
98.7	150.7	98.7	164.1	397.3	414.6	142.8	64.2	66.9	12.69
CONSOLIDATION PERIOD 20									
81.8	122.9	81.8	137.9	333.9	349.9	123.8	64.6	66.9	11.00
CONSOLIDATION PERIOD 70									
115.6	186.9	115.6	223.1	*****	593.9	270.1	68.4	66.9	24.01

SHEAR INDEX (N) = 1.40

COHESION/ TENSILE STRENGTH = 4.50


EFFECTIVE ANGLE FRICTION, DEG.
FF = material flow function
ff_s = mass flow hopper flow factor
ff_p = piping hopper flow factor
ff_d = doming hopper flow factor
MAX. TIME CONSOLIDATION
FF
ff_d
ff_s
ff_p
Figure A1
MATERIAL & HOPPER FLOW FACTORS
Sample No. 1A
HEMLOCK HOG FUEL
UNCONFINED YIELD STRENGTH g/cm²
MAJOR PRINCIPAL CONSOLIDATING STRESS, g/cm²

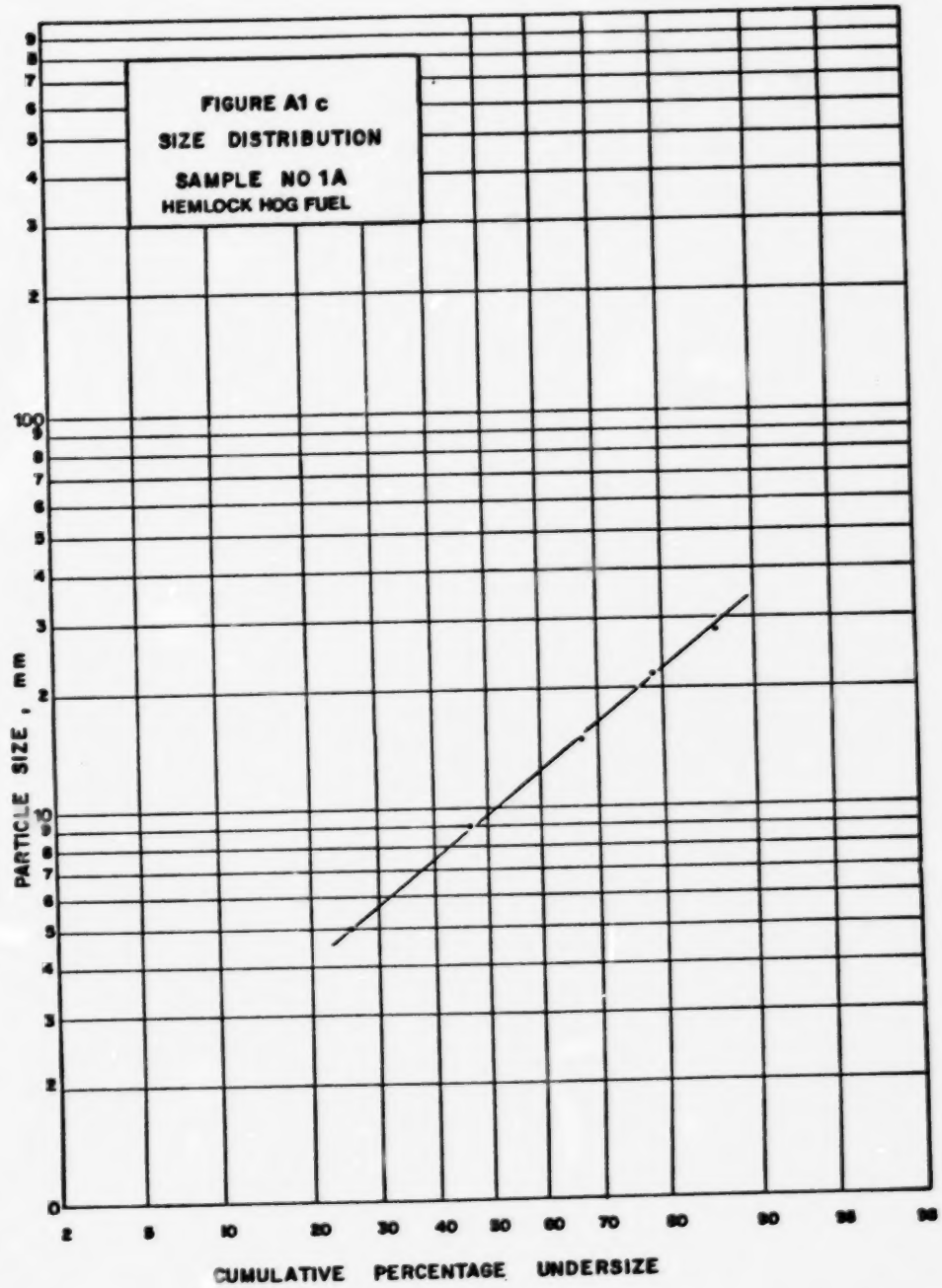


FIGURE A1 c
SIZE DISTRIBUTION
SAMPLE NO 1A
HEMLOCK HOG FUEL
PARTICLE SIZE , mm
CUMULATIVE PERCENTAGE UNDERSIZE

TABLE A1 (8)

COMPUTER ANALYSIS OF FLOW PROPERTIES

HEMLOCK HOG FUEL SAMPLE # 1B

SHEAR TEST RESULTS

CONSOLIDATION		YIELD	
NORMAL STRESS	SHEAR STRESS	NORMAL STRESS	SHEAR STRESS
G/SQ CM	G/SQ CM	G/SQ CM	G/SQ CM
48.1	70.1		
		4.2	12.1
		8.4	26.0
		16.8	49.5
		27.0	47.2
		33.7	70.9
		39.6	70.3
		48.1	70.1
59.9	94.6		
		4.2	22.2
		8.4	26.2
		16.8	39.4
		27.0	52.5
		43.8	86.1
		56.5	93.0
		59.9	94.6
81.8	145.1		
		4.2	28.5
		12.6	30.5
		27.0	54.9
		56.5	95.5
		59.9	113.9
		73.4	121.7
		81.8	145.1
98.7	159.1		
		4.2	23.1
		12.6	37.6
		27.0	75.2
		56.5	113.9
		73.4	122.6
		90.3	152.1
		98.7	159.1
115.6	180.3		
		4.2	19.6
		12.6	65.0
		27.0	118.6
		56.5	134.2
		81.8	161.5
		107.1	179.7
		115.6	180.3

TABLE A1 (b)

HEMLOCK HOG FUEL SAMPLE # 1B

FLOW PROPERTIES OF MATERIAL

CONSOLIDATION				FLOW PROPERTIES				
NORMAL STRESS	SHEAR STRESS	MAJ PRINC CONSOL'N STRESS	UNCONFIN YIELD STRESS	FLOW FUNC	EFFECT FRIC ANGLE	INTERNAL FRIC ANG AT FREE SURFACE	COHESION	TENSILE STRENGTH
G/SQ CM	G/SQ CM	G/SQ CM	G/SQ CM		DEG	DEG	G/SQ CM	G/SQ CM
48.1	70.1	176.9	102.4	1.73	66.6	62.06	10.12	2.02
59.9	94.6	218.4	125.3	1.74	66.3	62.06	12.38	2.47
81.8	145.1	301.8	175.2	1.72	66.6	62.06	17.32	3.46
98.7	159.1	358.8	205.1	1.75	66.2	62.06	20.28	4.05
115.6	180.3	458.8	287.0	1.60	68.6	62.06	28.37	5.67

SHEAR INDEX (N) = 1.59

YIELD LOCUS	PERCENT FIT
1	97.8
2	99.2
3	98.3
4	99.5
5	97.9

TABLE A1 (C)

WALL FRICTION TEST RESULTS

HEMLOCK HOG FUEL SAMPLE #1B

WALL MATERIAL - ULTRA HIGH MOLECULAR POLYMER

NORMAL STRESS G/SQ CM	SHEAR STRESS G/SQ CM
76.7	19.2
68.2	17.3
59.8	15.4
51.3	13.4
42.9	11.5
34.5	9.0
26.0	7.5
17.5	5.4
9.0	3.3
4.7	2.0

TABLE A1 (d)

COMPUTER ANALYSIS OF STORAGE AT REST

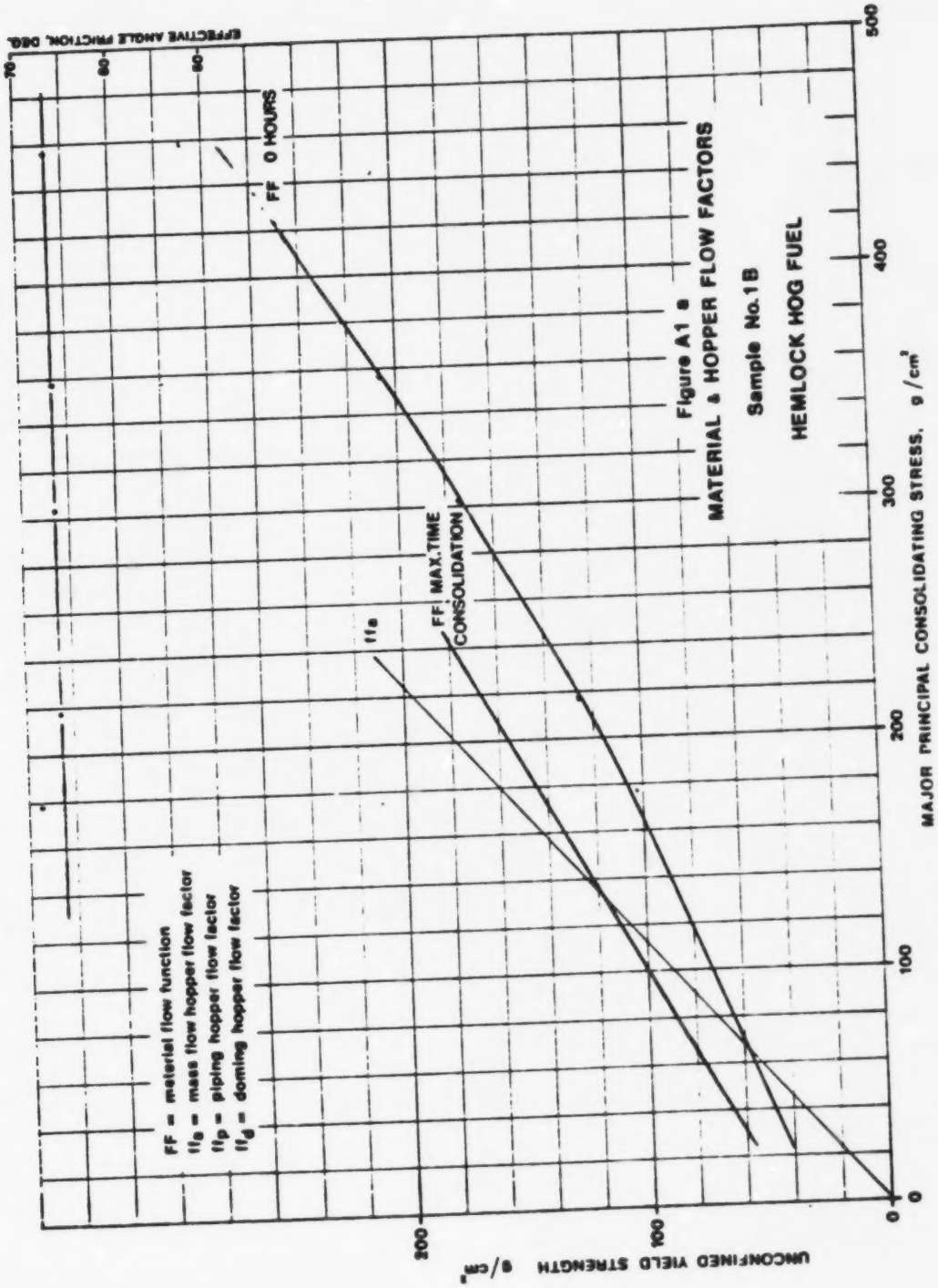
HEMLOCK HOG FUEL (SAMPLE # 1B)

TIME CONSOLIDATION RESULTS

CONSOLIDATION NORMAL STRESS	CONSOLIDATION SHEAR STRESS	YIELD POINT NORMAL STRESS	YIELD POINT SHEAR STRESS	FLOW PROPERTIES MAJ PRINC CONSOL'N STRESS INST	FLOW PROPERTIES MAJ PRINC CONSOL'N STRESS TIME	FLOW PROPERTIES UNCONFIN YIELD STRESS	FLOW PROPERTIES EFFECT FRIC ANGLE	FLOW PROPERTIES INTERNAL FRIC ANG AT FREE SURFACE	FLOW PROPERTIES COHESION
G/SQ CM	G/SQ CM	G/SQ CM	G/SQ CM	G/SQ CM	G/SQ CM	G/SQ CM	DEG	DEG	G/SQ CM
CONSOLIDATION PERIOD 1									
59.9	112.3	59.9	119.8	218.4	298.8	227.4	74.3	62.1	22.44
81.8	119.8	81.8	126.4	301.8	292.9	163.6	65.7	62.1	16.15
CONSOLIDATION PERIOD 16									
48.1	80.5	48.1	87.0	176.9	210.0	142.9	71.0	62.1	14.11
59.9	88.0	59.9	97.3	218.4	228.2	136.3	67.4	62.1	13.46
81.8	122.0	81.8	139.5	301.8	330.9	209.7	69.0	62.1	20.70
98.7	156.0	98.7	179.7	358.8	434.6	297.9	71.2	62.1	29.40
115.6	175.7	115.6	190.3	458.8	447.6	271.7	67.9	62.1	26.82
CONSOLIDATION PERIOD 44									
48.1	80.7	48.1	85.1	176.9	204.1	135.4	70.3	62.1	13.37
CONSOLIDATION PERIOD 100									
59.9	95.1	59.9	105.0	218.4	251.0	164.5	69.9	62.1	16.24

SHEAR INDEX (N) = 1.59

COHESION/ TENSILE STRENGTH = 5.00


EFFECTIVE ANGLE FRICTION, DEG.
70
60
50
FF 0 HOURS
FF MAX. TIME CONSOLIDATION
Π_a
FF = material flow function
Π_s = mass flow hopper flow factor
Π_p = piping hopper flow factor
Π_d = doming hopper flow factor
Figure A1 a
MATERIAL & HOPPER FLOW FACTORS
Sample No. 1B
HEMLOCK HOG FUEL
UNCONFINED YIELD STRENGTH g/cm²
200
100
0
0
100
200
300
400
500
MAJOR PRINCIPAL CONSOLIDATING STRESS, g/cm²

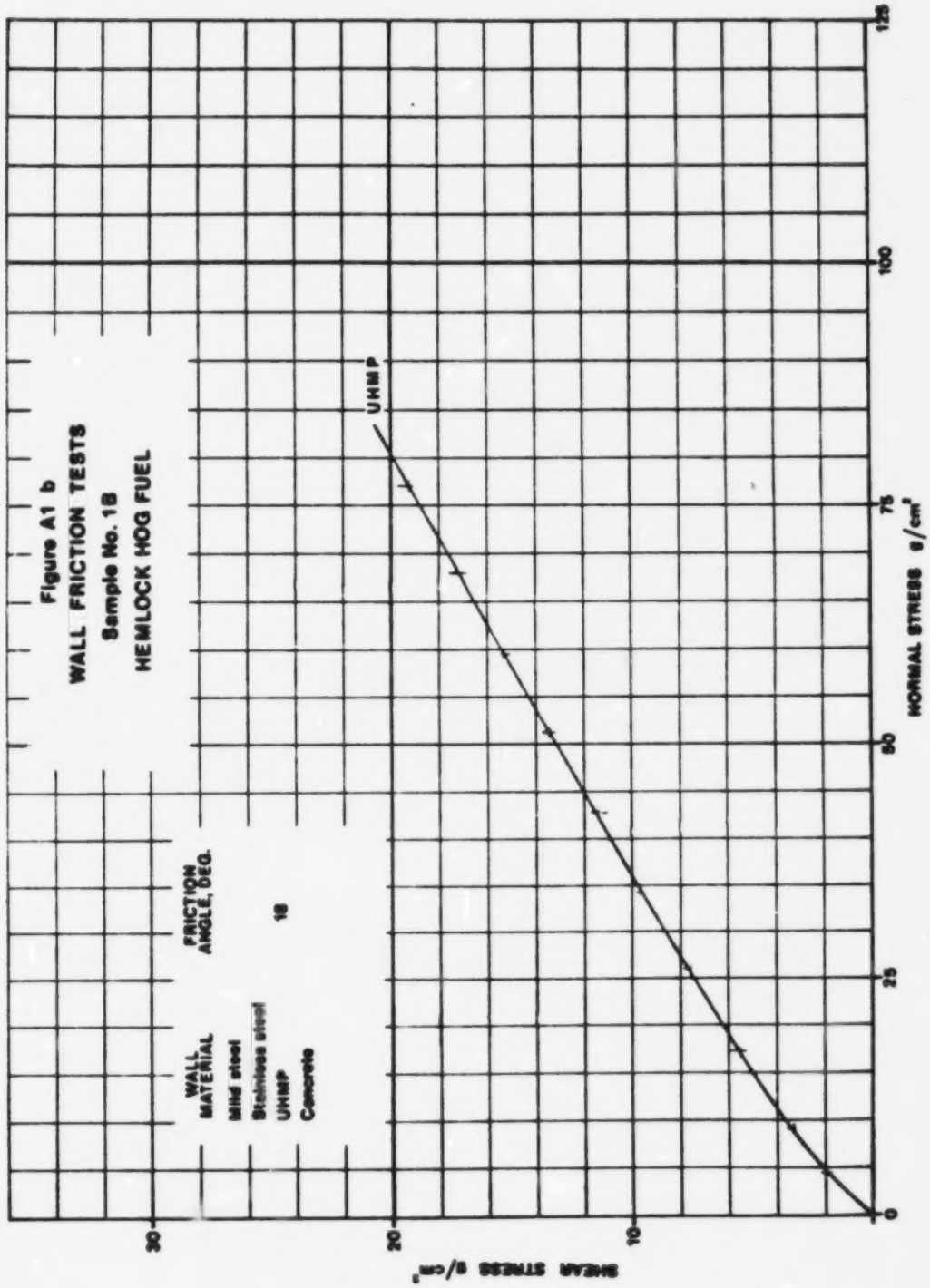


Figure A1 b
WALL FRICTION TESTS
Sample No. 18
HEMLOCK HOG FUEL
WALL MATERIAL
Mild steel
Stainless steel
UHMP
Concrete
FRICTION ANGLE, DEG.
18
UHMP
SHEAR STRESS g/cm²
NORMAL STRESS g/cm²
0
10
20
30
25
50
75
100
125

TABLE A2 (a)

COMPUTER ANALYSIS OF FLOW PROPERTIES

STRINGY CEDAR BARK SAMPLE #2

SHEAR TEST RESULTS

CONSOLIDATION		YIELD	
NORMAL STRESS G/SQ CM	SHEAR STRESS G/SQ CM	NORMAL STRESS G/SQ CM	SHEAR STRESS G/SQ CM
48.1	73.9	4.2	12.4
		8.4	24.0
		16.8	34.5
		27.0	52.0
		33.7	64.1
		39.6	70.1
		48.1	73.9
59.9	120.1	4.2	15.0
		8.4	44.6
		16.8	49.0
		27.0	53.7
		43.8	93.8
		56.5	105.7
		59.9	120.1
81.8	145.1	4.2	20.8
		12.6	41.6
		27.0	57.9
		56.5	65.1
		59.9	89.2
		73.4	120.1
		81.8	145.1
98.7	161.6	4.2	23.2
		12.6	34.7
		27.0	74.3
		56.5	112.2
		73.4	148.2
		90.3	149.1
		98.7	161.6
115.6	190.3	4.2	22.8
		12.6	76.8
		27.0	124.2
		56.5	103.8
		81.8	138.8
		107.1	172.8
		115.6	190.3

TABLE A2 (b)

STRINGY CEDAR BARK SAMPLE #2

FLOW PROPERTIES OF MATERIAL

CONSOLIDATION				FLOW PROPERTIES				
NORMAL STRESS	SHEAR STRESS	MAJ PRINC CONSOL'N STRESS	UNCONFIN YIELD STRESS	FLOW FUNC	EFFECT FRIC ANGLE	INTERNAL FRIC ANG AT FREE SURFACE	COHESION	TENSILE STRENGTH
G/SQ CM	G/SQ CM	G/SQ CM	G/SQ CM		DEG	DEG	G/SQ CM	G/SQ CM
48.1	73.9	173.8	90.4	1.92	65.2	63.36	8.58	1.69
59.9	120.1	267.1	172.3	1.55	70.5	63.36	16.36	3.21
81.8	145.1	275.7	131.9	2.09	63.3	63.36	12.52	2.46
98.7	161.6	379.1	210.7	1.80	66.8	63.36	20.01	3.93
115.6	190.3	443.8	246.5	1.80	66.8	63.36	23.41	4.60

SHEAR INDEX (N) = 1.57

YIELD LOCUS	PERCENT FIT
1	99.2
2	98.1
3	95.5
4	99.2
5	96.2

TABLE A2 (C)

WALL FRICTION TEST RESULTS

STRINGY CEDAR BARK SAMPLE #2

WALL MATERIAL - ULTRA HIGH MOLECULAR POLYMER

NORMAL STRESS G/SQ CM	SHEAR STRESS G/SQ CM
75.4	21.9
66.9	17.6
58.4	15.6
50.0	13.5
41.6	11.5
33.2	9.5
24.7	7.4
16.2	5.4
7.7	3.1
3.3	1.7

WALL MATERIAL - GLASS COATED STEEL

NORMAL STRESS G/SQ CM	SHEAR STRESS G/SQ CM
75.4	21.5
66.9	18.1
58.4	15.8
50.0	13.8
41.6	11.7
33.2	9.7
24.7	7.6
16.2	5.4
7.7	3.1
3.3	1.7

TABLE A2 (d)

COMPUTER ANALYSIS OF STORAGE AT REST

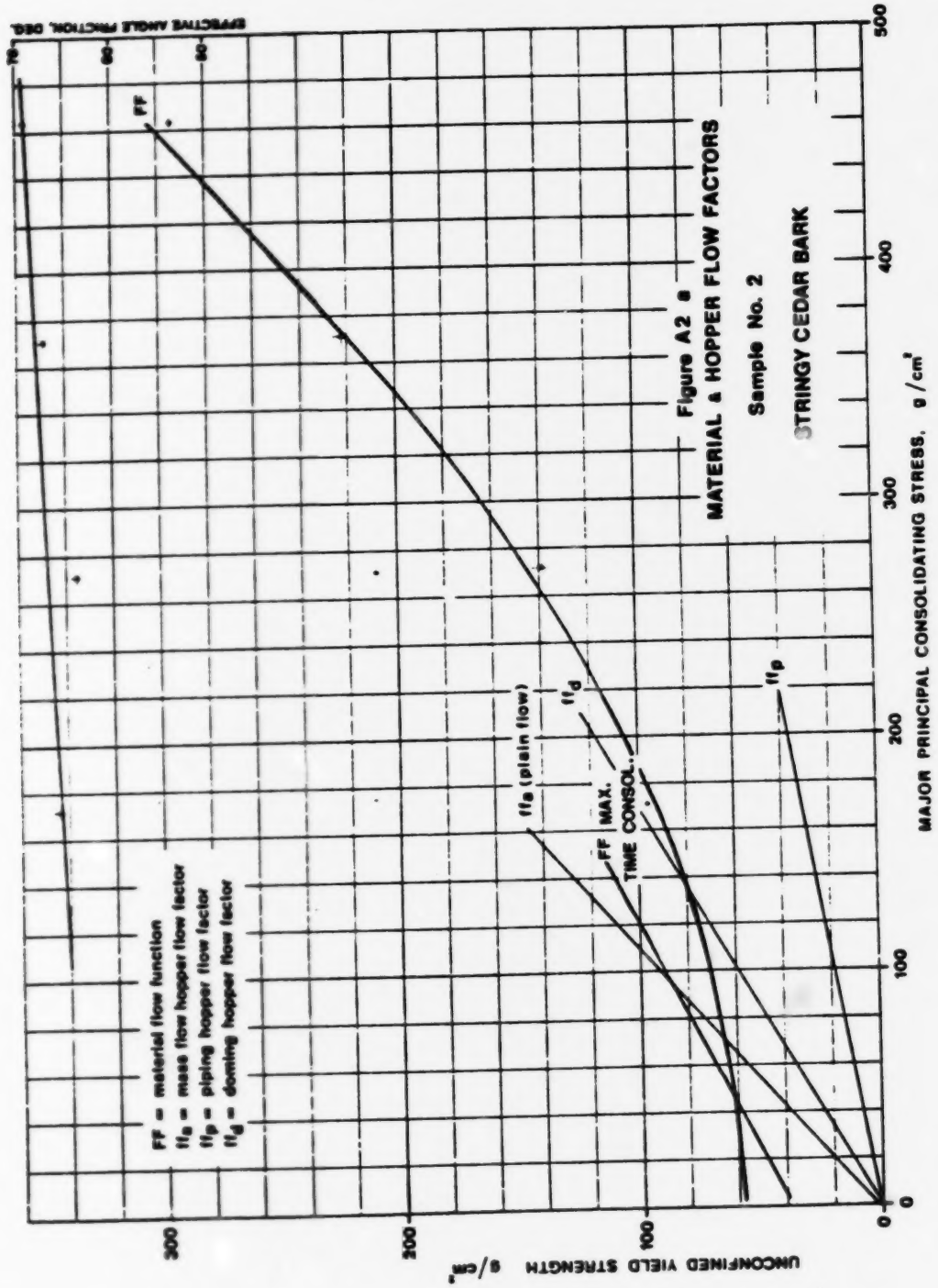
STRINGY CEDAR BARK SAMPLE #2

TIME CONSOLIDATION RESULTS

CONSOLIDATION NORMAL STRESS	CONSOLIDATION SHEAR STRESS	YIELD POINT NORMAL STRESS	YIELD POINT SHEAR STRESS	FLOW PROPERTIES: MAJ PRINC CONSOL'N STRESS INST	MAJ PRINC CONSOL'N STRESS TIME	UNCONFIN YIELD STRESS	EFFECT FRIC ANGLE	INTERNAL FRIC ANG AT FREE SURFACE	COHESION
G/SQ CM	G/SQ CM	G/SQ CM	G/SQ CM	G/SQ CM		G/SQ CM	DEG	DEG	G/SQ CM
CONSOLIDATION PERIOD 1 HOUR									
48.1	84.2	48.1	84.9	173.8	205.2	127.8	69.5	63.3	12.16
48.1	82.1	48.1	82.2	173.8	197.0	118.0	68.5	63.3	11.23
98.7	168.5	98.7	169.1	379.1	405.3	243.0	68.6	63.3	23.13
115.6	165.4	115.6	170.7	443.8	395.0	193.7	63.7	63.3	18.44
CONSOLIDATION PERIOD 5 HOURS									
59.9	105.1	59.9	113.7	267.1	281.3	191.3	71.8	63.3	18.20
59.9	109.2	59.9	111.3	67.1	273.5	181.4	71.2	63.3	17.27
CONSOLIDATION PERIOD 16 HOURS									
48.1	81.1	48.1	84.4	173.8	203.6	125.9	69.3	63.3	11.98
59.9	90.2	59.9	96.2	267.1	226.8	125.0	66.5	63.3	11.90
81.8	129.2	81.8	141.6	275.7	340.5	206.9	68.9	63.3	19.69
98.7	134.8	98.7	148.5	379.1	344.9	173.8	64.4	63.3	16.54
115.6	183.5	115.6	198.1	443.8	474.9	285.0	68.6	63.3	27.12
CONSOLIDATION PERIOD 26 HOURS									
59.9	65.6	59.9	72.0	267.1	163.0	58.3	56.8	63.3	5.55
CONSOLIDATION PERIOD 65 HOURS									
48.1	74.6	48.1	81.6	173.8	195.1	115.7	68.3	63.3	11.01
81.8	126.4	81.8	139.2	275.7	332.8	197.7	68.3	63.3	18.82

SHEAR INDEX (N) = 1.57

COHESION/ TENSILE STRENGTH = 5.09


EFFECTIVE ANGLE FRICTION, DEG.
UNCONFINED YIELD STRENGTH g/cm²
MAJOR PRINCIPAL CONSOLIDATING STRESS, g/cm²
FF = material flow function
ff_s = mass flow hopper flow factor
ff_p = piping hopper flow factor
ff_d = doming hopper flow factor
FF
ff_s (plain flow)
ff_d
ff_p
FF MAX.
TIME CONSOL.
Figure A2 e
MATERIAL & HOPPER FLOW FACTORS
Sample No. 2
STRINGY CEDAR BARK

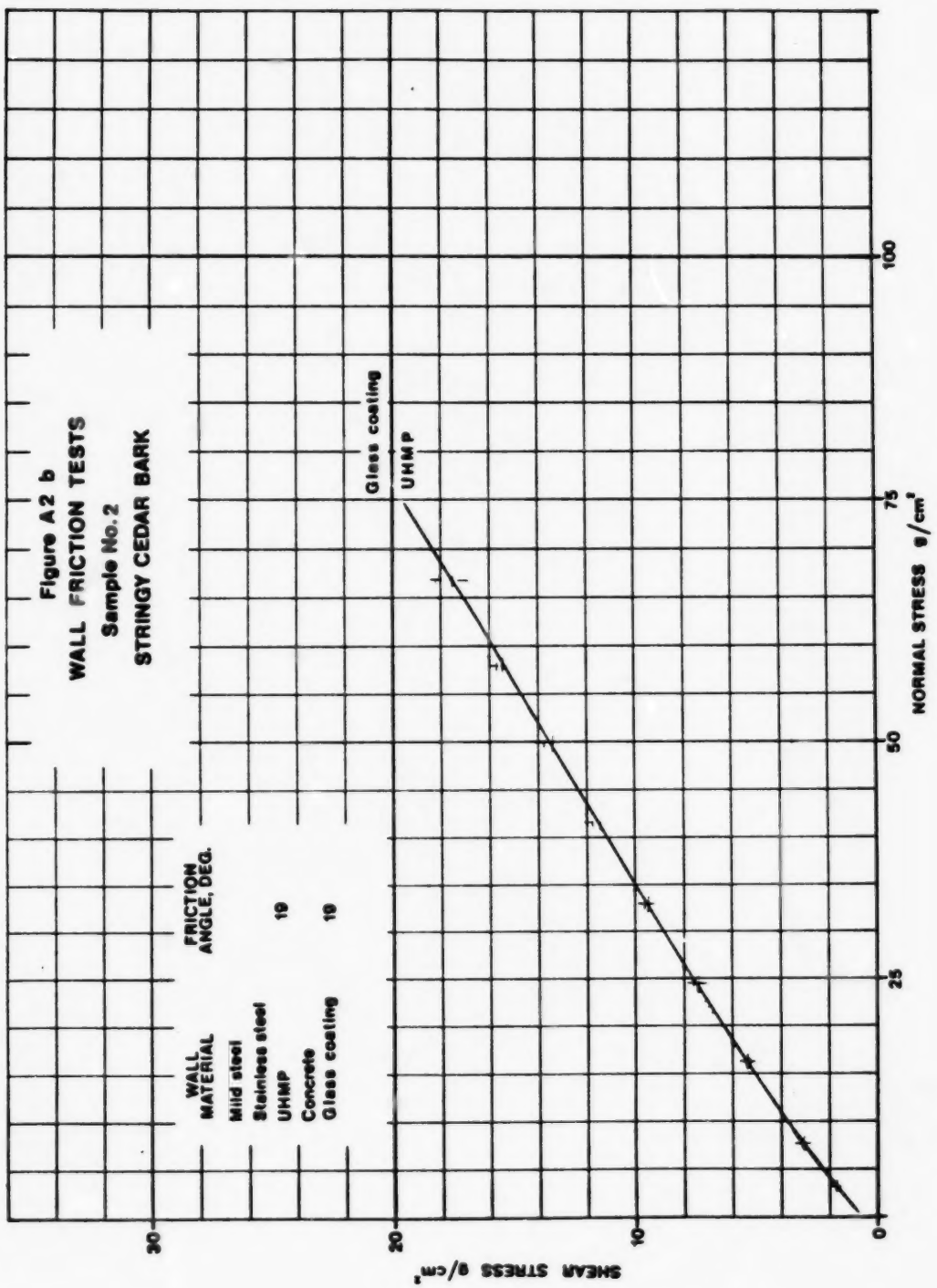


Figure A2 b
WALL FRICTION TESTS
Sample No. 2
STRINGY CEDAR BARK
WALL MATERIAL
FRICTION ANGLE, DEG.
Mild steel
Stainless steel 19
UHMP
Concrete
Glass coating 19
Glass coating
UHMP
SHEAR STRESS g/cm²
NORMAL STRESS g/cm²
0
10
20
30
25
50
75
100

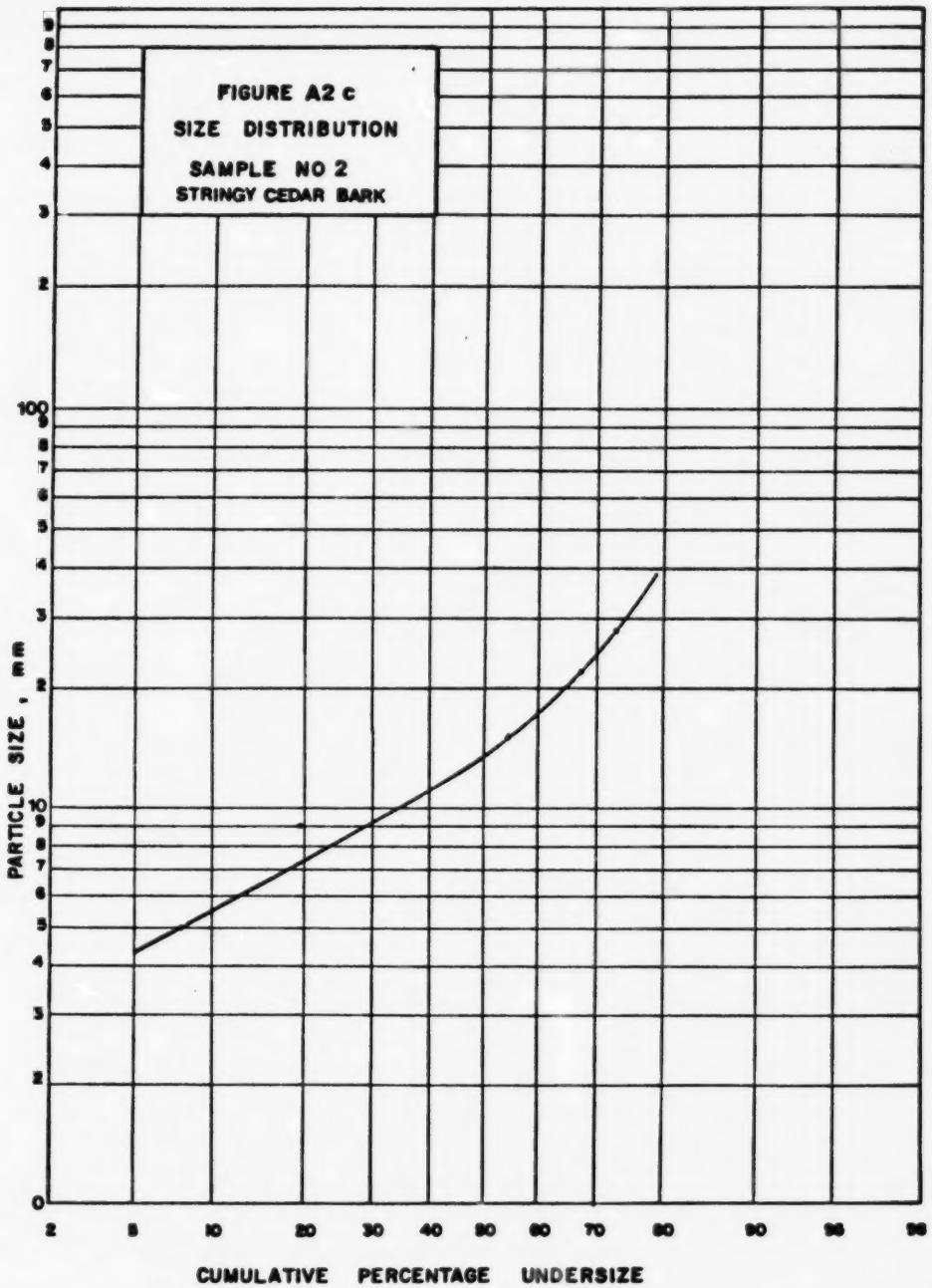


FIGURE A2 c
SIZE DISTRIBUTION
SAMPLE NO 2
STRINGY CEDAR BARK
PARTICLE SIZE , mm
CUMULATIVE PERCENTAGE UNDERSIZE
2
5
10
20
30
40
50
60
70
80
90
95
98

TABLE A3 (8)

COMPUTER ANALYSIS OF FLOW PROPERTIES

DRY CEDAR HOG FUEL SAMPLE #3

SHEAR TEST RESULTS

CONSOLIDATION		YIELD	
NORMAL STRESS G/SQ CM	SHEAR STRESS G/SQ CM	NORMAL STRESS G/SQ CM	SHEAR STRESS G/SQ CM
27.0	34.0		
		2.5	7.4
		4.2	11.6
		8.4	15.2
		12.6	22.3
		16.8	31.2
		24.4	32.9
		27.0	34.0
48.1	53.0		
		4.2	13.5
		8.4	15.4
		16.8	31.3
		27.0	42.0
		33.7	43.5
		39.6	48.0
		48.1	53.0
59.9	90.4		
		4.2	16.3
		8.4	23.0
		16.8	26.8
		27.0	38.5
		43.8	69.1
		56.5	81.4
		59.9	90.4
81.8	110.8		
		4.2	22.4
		12.6	29.6
		27.0	58.7
		56.5	79.5
		59.9	99.7
		73.4	103.7
		81.8	110.8
98.7	153.5		
		4.2	19.3
		12.6	34.8
		27.0	77.5
		56.5	100.5
		73.4	135.7
		90.3	147.0
		98.7	153.5
115.6	168.5		
		4.2	21.7
		12.6	36.4
		27.0	71.5
		56.5	114.8
		81.8	142.9
		107.1	162.2
		115.6	168.5

TABLE A3 (b)

DRY CEDAR HOG FUEL SAMPLE #3

FLOW PROPERTIES OF MATERIAL

CONSOLIDATION				FLOW PROPERTIES				
NORMAL STRESS	SHEAR STRESS	MAJ PRINC CONSOL'N STRESS	UNCONFIN YIELD STRESS	FLOW FUNC	EFFECT FRIC ANGLE	INTERNAL FRIC ANG AT FREE SURFACE	COHESION	TENSILE STRENGTH
G/SQ CM	G/SQ CM	G/SQ CM	G/SQ CM		DEG	DEG	G/SQ CM	G/SQ CM
27.0	34.0	86.3	26.4	3.27	58.6	63.42	2.69	.68
48.1	53.0	131.7	29.8	4.42	54.0	63.42	3.05	.77
59.9	90.4	197.7	63.8	3.10	59.5	63.42	6.52	1.64
81.8	110.8	268.3	85.5	3.14	59.3	63.42	8.74	2.21
98.7	153.5	380.1	156.8	2.42	63.5	63.42	16.03	4.04
115.6	168.5	419.1	157.7	2.66	61.9	63.42	16.13	4.07

SHEAR INDEX (N) = 1.42

YIELD LOCUS	PERCENT FIT
1	98.9
2	99.3
3	98.6
4	99.4
5	99.4
6	99.7

TABLE A3 (c)

WALL FRICTION TEST RESULTS

DRY CEDAR HOG FUEL SAMPLE #3

WALL MATERIAL - GLASS COATED STEEL

NORMAL STRESS G/SQ CM	SHEAR STRESS G/SQ CM
75.3	19.2
66.8	16.4
58.3	14.3
49.8	12.4
41.4	10.6
33.0	8.6
24.5	6.9
16.0	4.8
7.5	2.8
3.2	1.7

TABLE A3 (d)

COMPUTER ANALYSIS OF STORAGE AT REST

DRY CEDAR HOG FUEL SAMPLE #3

TIME CONSOLIDATION RESULTS

CONSOLIDATION NORMAL STRESS	CONSOLIDATION SHEAR STRESS	YIELD POINT NORMAL STRESS	YIELD POINT SHEAR STRESS	FLOW PROPERTIES: MAJ PRINC CONSOL'N STRESS INST	MAJ PRINC CONSOL'N STRESS TIME	UNCONFIN YIELD STRESS	EFFECT FRIC ANGLE	INTERNAL FRIC ANG AT FREE SURFACE	COHESION
G/SQ CM	G/SQ CM	G/SQ CM	G/SQ CM	G/SQ CM	G/SQ CM	G/SQ CM	DEG	DEG	G/SQ CM
CONSOLIDATION PERIOD 2									
59.9	77.9	59.9	84.2	197.7	201.4	64.9	59.8	63.7	6.56
CONSOLIDATION PERIOD 3									
81.8	119.2	81.8	122.9	268.3	297.8	109.2	61.9	63.7	11.03
98.7	176.3	98.7	192.2	380.1	501.2	289.1	69.8	63.7	29.21
CONSOLIDATION PERIOD 16									
27.0	35.4	27.0	44.6	86.3	110.5	48.3	64.8	63.7	4.88
59.9	83.4	59.9	93.4	197.7	228.1	89.7	63.0	63.7	9.06
115.6	167.9	115.6	171.3	419.1	413.7	147.8	61.5	63.7	14.93

SHEAR INDEX (N) = 1.42

COHESION/ TENSILE STRENGTH = 4.00

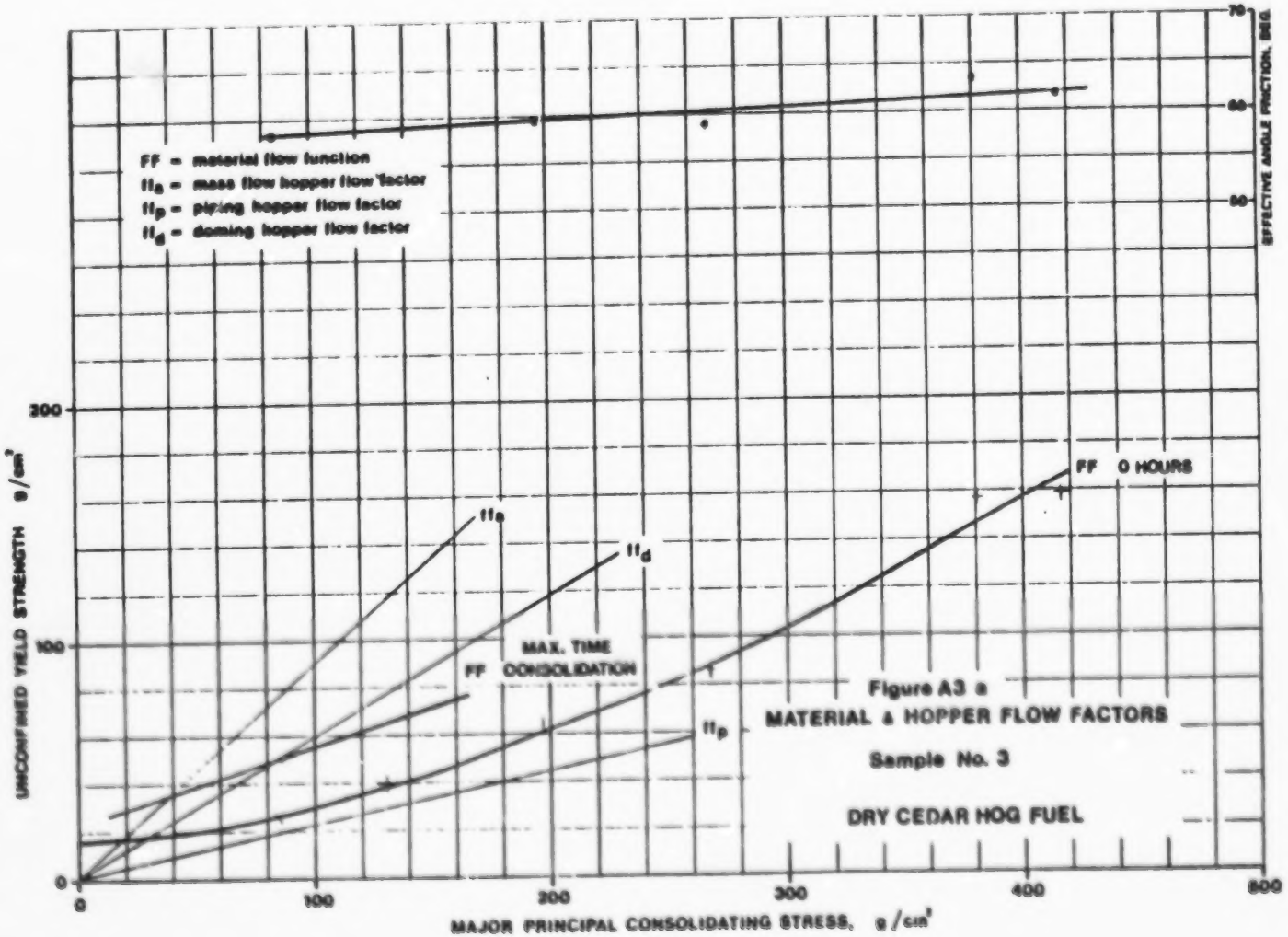


Figure A3 a
MATERIAL & HOPPER FLOW FACTORS
Sample No. 3

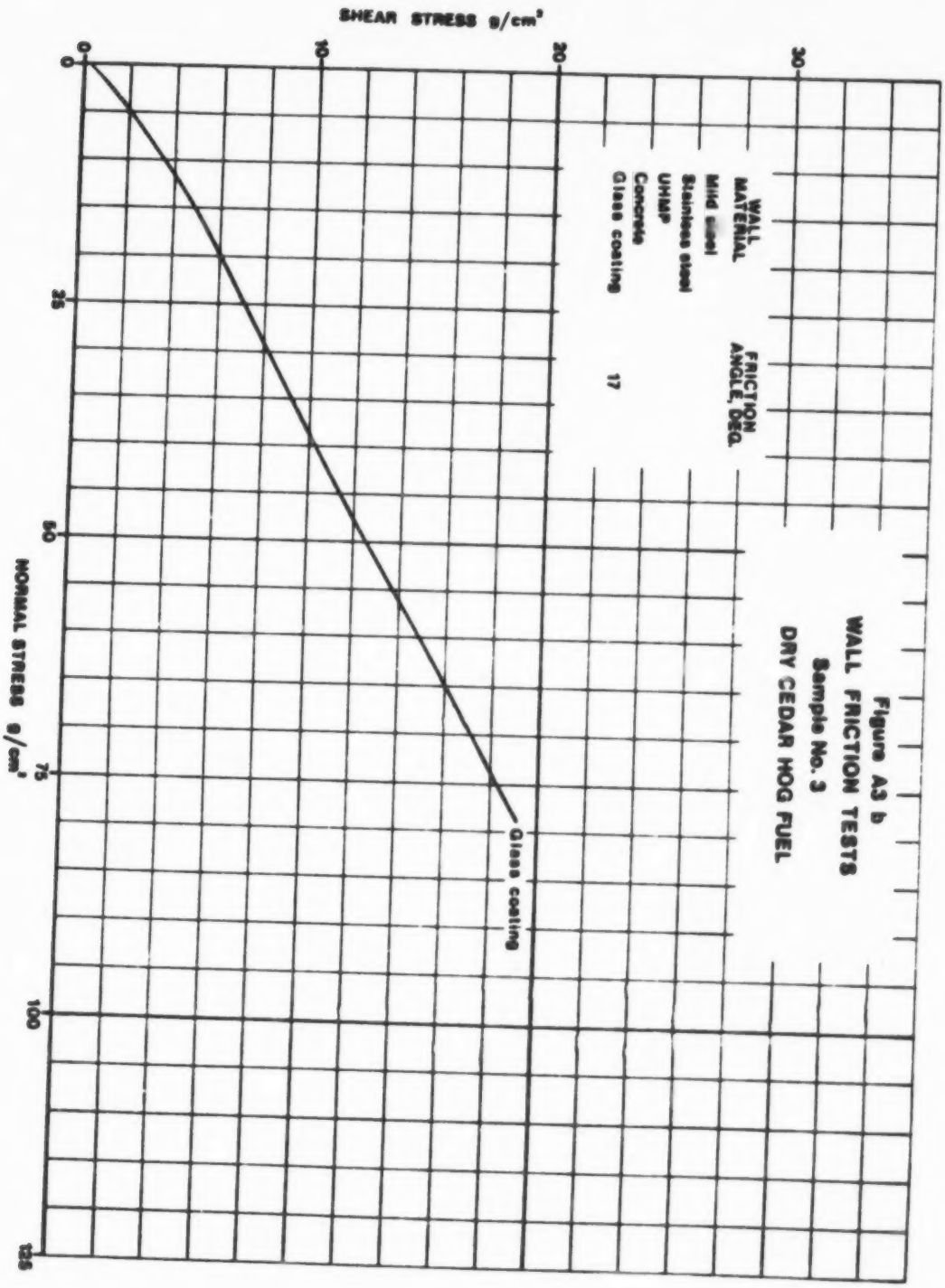


Figure A3 b
WALL FRICTION TESTS
Sample No. 3
DRY CEDAR HOG FUEL

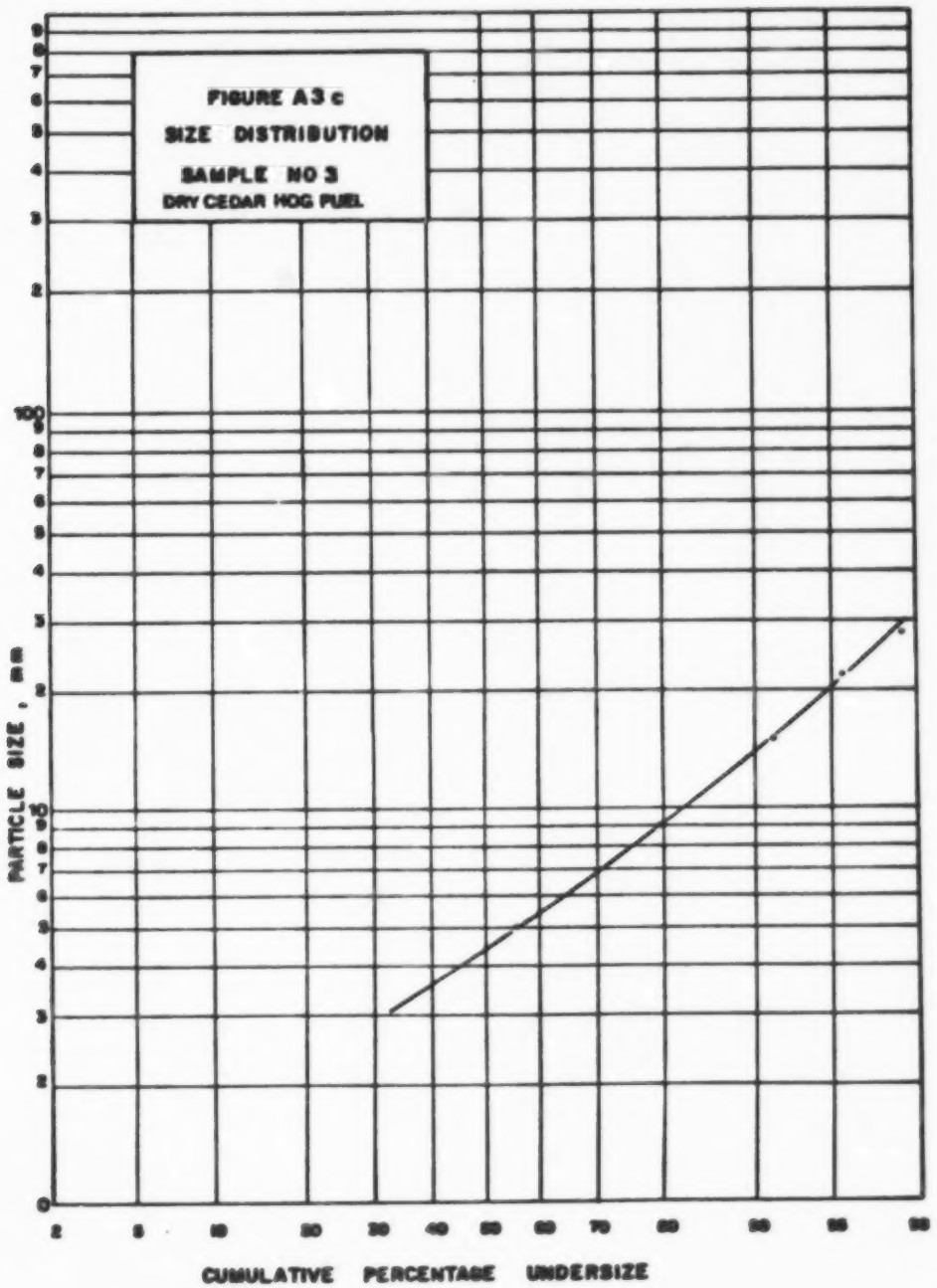


FIGURE A3 c
SIZE DISTRIBUTION
SAMPLE NO 3
DRY CEDAR HOG FUEL
PARTICLE SIZE , mm
CUMULATIVE PERCENTAGE UNDERSIZE

TABLE A4 (a)

COMPUTER ANALYSIS OF FLOW PROPERTIES

CEDAR WOOD CHIPS SAMPLE #4

SHEAR TEST RESULTS

CONSOLIDATION		YIELD	
NORMAL STRESS G/SQ CM	SHEAR STRESS G/SQ CM	NORMAL STRESS G/SQ CM	SHEAR STRESS G/SQ CM
27.0	39.4		
		2.5	6.9
		4.2	10.2
		8.4	17.6
		12.6	38.2
		16.8	22.2
		24.4	40.2
		27.0	39.4
48.1	75.8		
		4.2	11.0
		8.4	19.0
		16.8	34.4
		27.0	35.8
		33.7	48.8
		39.6	71.1
		48.1	75.8
59.9	103.2		
		4.2	9.0
		8.4	19.0
		16.8	37.3
		27.0	41.2
		43.8	73.3
		56.5	93.0
		59.9	103.2
81.8	121.4		
		4.2	17.1
		12.6	30.0
		27.0	63.6
		56.5	83.0
		59.9	84.1
		73.4	109.3
		81.8	121.4
98.7	144.5		
		4.2	16.3
		12.6	40.7
		27.0	63.0
		56.5	100.3
		73.4	118.6
		90.3	122.3
		98.7	144.5
115.6	167.5		
		4.2	11.9
		12.6	49.5
		27.0	69.5
		56.5	102.5
		81.8	130.4
		107.1	143.5
		115.6	167.5

TABLE A4 (b)

CEDAR WOOD CHIPS SAMPLE #4

FLOW PROPERTIES OF MATERIAL

CONSOLIDATION				FLOW PROPERTIES				
NORMAL STRESS	SHEAR STRESS	MAJ PRINC CONSOL'N STRESS	UNCONFIN YIELD STRESS	FLOW FUNC	EFFECT FRIC ANGLE	INTERNAL FRIC ANG AT FREE SURFACE	COHESION	TENSILE STRENGTH
G/SQ CM	G/SQ CM	G/SQ CM	G/SQ CM		DEG	DEG	G/SQ CM	G/SQ CM
27.0	39.4	102.1	34.0	3.00	62.1	65.10	3.27	.79
48.1	75.8	170.2	50.7	3.36	60.5	65.10	4.88	1.18
59.9	103.2	227.8	76.5	2.98	62.2	65.10	7.36	1.79
81.8	121.4	278.6	77.5	3.60	59.5	65.10	7.46	1.81
98.7	144.5	344.0	99.7	3.45	60.1	65.10	9.59	2.33
115.6	167.5	396.3	111.6	3.55	59.7	65.10	10.74	2.61

SHEAR INDEX (N) = 1.40

YIELD LOCUS	PERCENT FIT
1	93.9
2	97.5
3	98.2
4	99.2
5	99.6
6	99.3

TABLE A4 (c)

WALL FRICTION TEST RESULTS

CEDAR WOOD CHIPS SAMPLE #4

WALL MATERIAL - GLASS COATED STEEL

NORMAL STRESS G/SQ CM	SHEAR STRESS G/SQ CM
75.3	17.4
66.8	14.8
58.3	12.7
49.8	10.9
41.4	9.1
33.0	7.3
24.5	5.6
16.0	3.9
7.5	2.0
3.2	1.1

TABLE A4 (d)

COMPUTER ANALYSIS OF STORAGE AT REST

CEDAR CHIPS SAMPLE 84

TIME CONSOLIDATION RESULTS

CONSOLIDATION STRESS		YIELD POINT		<----------FLOW PROPERTIES----------				
NORMAL STRESS	SHEAR STRESS	NORMAL STRESS	SHEAR STRESS	MAJ PRINC CONSOL'N STRESS INST	MAJ PRINC CONSOL'N STRESS TIME	UNCONFIN YIELD STRESS	EFFECT FRIC ANGLE	INTERNAL FRIC ANG AT FREE SURFACE	COHESION
G/SQ CM	G/SQ CM	G/SQ CM	G/SQ CM	G/SQ CM		G/SQ CM	DEG	DEG	G/SQ CM
CONSOLIDATION PERIOD 4									
27.0	52.3	27.0	59.8	102.1	165.8	106.3	72.9	65.0	10.29
81.8	117.0	81.8	132.3	278.6	329.6	122.4	63.6	65.0	11.84
CONSOLIDATION PERIOD 15									
81.8	126.0	81.8	133.5	278.6	333.6	126.2	63.9	65.0	12.21

SHEAR INDEX (N) = 1.40

COHESION/ TENSILE STRENGTH = 4.10

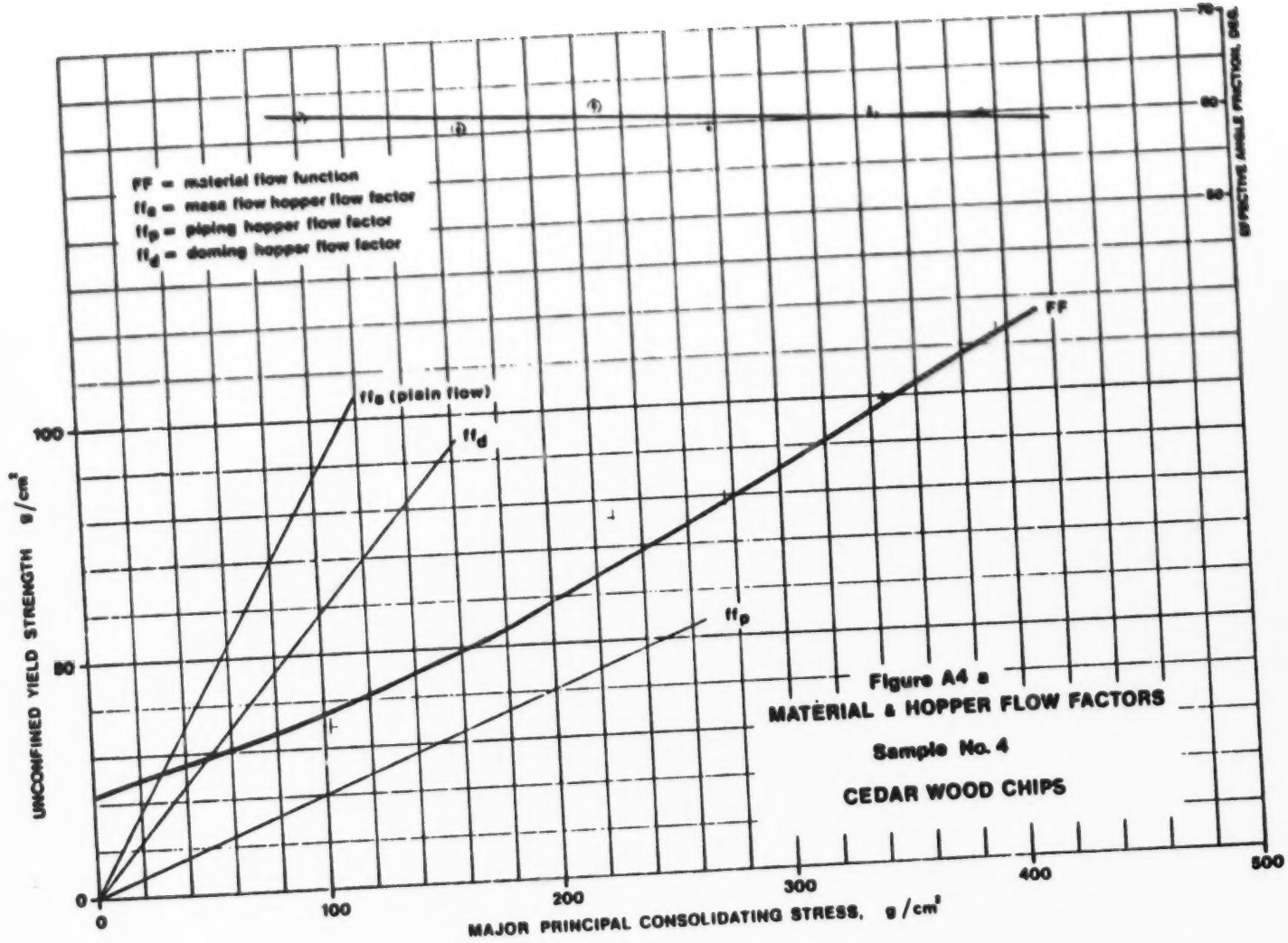


Figure A4 a
MATERIAL & HOPPER FLOW FACTORS
Sample No. 4
CEDAR WOOD CHIPS

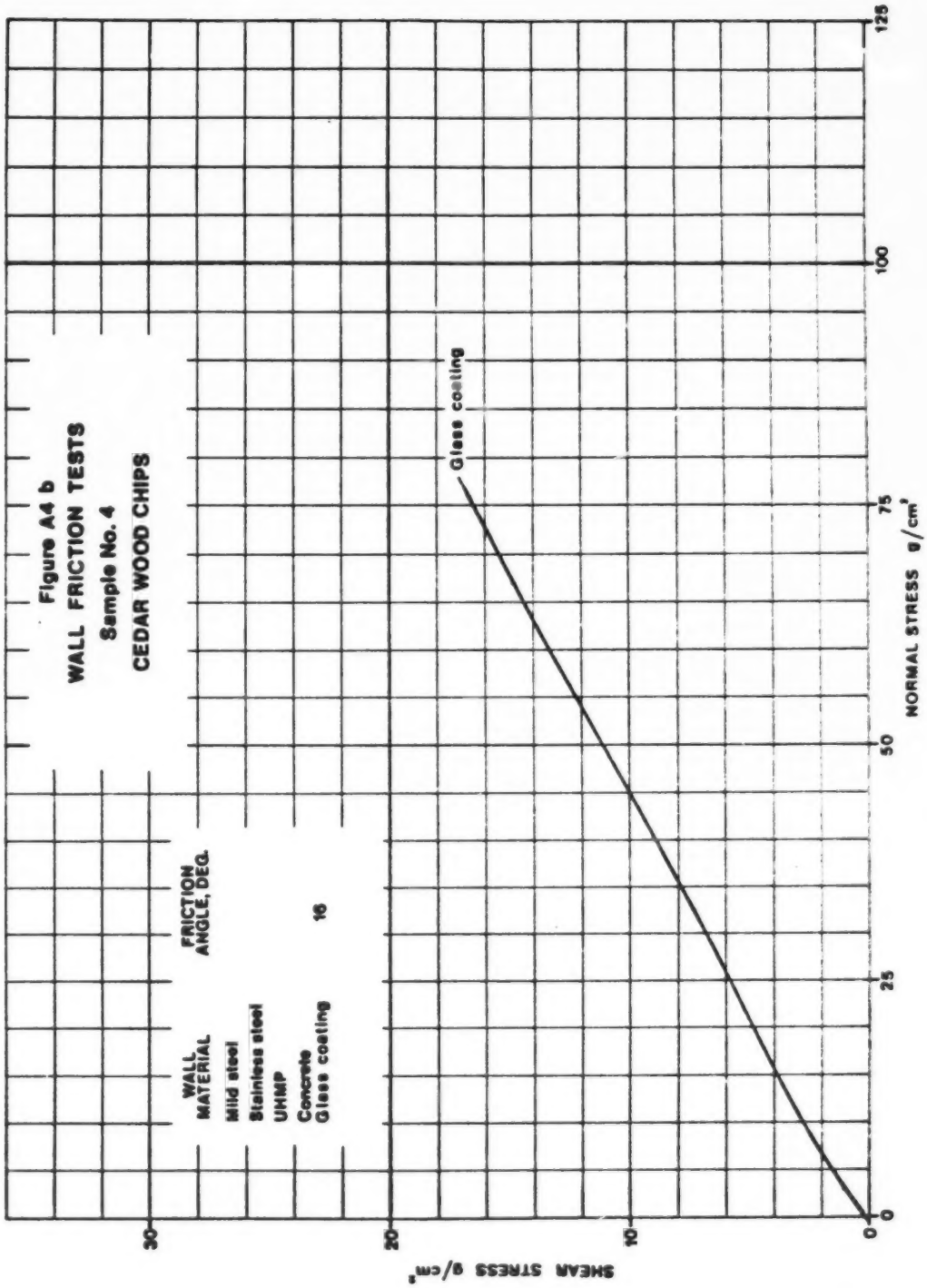


Figure A4 b
WALL FRICTION TESTS
Sample No. 4
CEDAR WOOD CHIPS
WALL MATERIAL
FRICTION ANGLE, DEG.
Mild steel
Stainless steel
UHMP
Concrete
Glass coating 16
Glass coating
SHEAR STRESS g/cm²
NORMAL STRESS g/cm²
0
10
20
30
0
25
50
75
100
125

POOR

QUALITY

ORIGINAL